the exponential factor in equation 4.2, where factors other than $E_t$ do not contribute significantly to the temperature dependence. Since the temperature dependence of $E_t$ is dominated by the bandgap temperature dependence, the same is expected for the temperature dependence of the tunneling current, resulting in a concave shape of tunneling current vs. temperature on a linear scale, as seen in Fig. 4.6a. When plotted on a logarithmic scale, the tunneling current is expected to have the following form:

$$\log I_t \propto E_t \propto E_G$$  \hspace{1cm} (4.4)

If instead of temperature, the corresponding bandgap is used as $x$-axis and the tunneling current is plotted on a logarithmic scale, a linear dependence vs. bandgap is expected resulting from the linear dependence on $E_t$ (equation 4.4). This is shown in Fig. 4.6b. We have assumed that the Si$_{1-x}$Ge$_x$ bandgap has the same temperature dependence as that of Si (given in ref. [86]), i.e. that the Si/Si$_{1-x}$Ge$_x$ bandgap offset (105meV for $x=0.15$) is temperature independent. The same method to identify excess tunneling current was used in ref. [81].

### 4.3 Discussion

For the same n-type doping, the tunneling currents in our devices are approximately three orders of magnitude lower than those of the ion implanted devices previously reported [78]. If the implanted junctions were somewhat compensated due to the non-abrupt implantation profiles, the actual junction doping would be less than indicated, making the RTCVD results even better in comparison. Since the tunneling current is mediated by midgap states at the junction, the vast reduction in tunneling currents of the devices fabricated by RTCVD implies a commensurate reduction of density of defects at the interface. This may be due to the absence of residual implant-related damage in the RTCVD junctions, and these results indicate high quality of epitaxial
Figure 4.6: a) Typical current vs. temperature dependence of a heavily doped SiGe/Si device \((N_D = 1 \times 10^{19} \text{ cm}^{-3}, V_a = 0.32 \text{V}, A = 3.25 \times 10^{-4} \text{ cm}^2)\). b) Current vs. Si\(_{0.85}\)Ge\(_{0.15}\) bandgap of the same device. The data confirms the expected shape of excess tunneling current.
4. Tunneling Current in p+ – n+ Junctions

interfaces. We have no independent measurement of the midgap state densities at the junction to confirm this hypothesis, however. Base-emitter junctions are often formed by diffusion from doped polysilicon instead of ion implantation in present-day technology. Significant tunneling currents have also been observed in base-emitter junctions formed by a poly-Si emitter process [80, 81], but no systematic data on tunneling current densities as the function of doping at the junction, like that of [78], has been reported.

The implications of these results for HBT performance are shown in Fig. 4.7. It is shown how the tunneling current is predicted to limit the current gain in a Si/Si$_{0.85}$Ge$_{0.15}$/Si HBT with a base doping $5 \times 10^{19}$ cm$^{-3}$ and a basewidth of 500Å, as the emitter doping is increased. Without the presence of tunneling, the gain would follow the ideal curve shown in the figure. At higher emitter doping levels, the ideal curve bends due to the bandgap narrowing in the heavily doped silicon emitter. The minority carrier parameters of del Alamo [84] are used to model n-Si emitter. With tunneling, the gain curves are predicted to drop rapidly after a certain doping is reached since tunneling causes a significant increase in the base current. The effects of the tunneling levels in epitaxially grown junctions are contrasted to those in implanted junctions, previously reported. The reduction in parasitic tunneling current at the same doping level that we observed predicts a shift towards higher emitter doping and an increase in the peak gain. The low tunneling current enables high gain to be maintained to higher base doping levels, enabling reduced base resistances and increased Early voltages.

To avoid excess tunneling currents, often proposed device structures have a reduced emitter doping at the base-emitter junction or a lighter doped emitter spacer layer [87]. However, the lighter doped ($1 \times 10^{18}$ cm$^{-3}$ or less) emitter layer could lead to a degradation of high speed performance due to an increase in the emitter storage time, normally negligible in heavily doped emitters [47].
4. Tunneling Current in p+ – n+ Junctions

Figure 4.7: Calculated effects of the tunneling current on the gain of Si/Si$_{1-x}$Ge$_x$/Si HBT's as the emitter doping is increased. Both curves based on the ion implantation results and this data are given for comparison, as well as the ideal curve (no tunneling).
4. Tunneling Current in $p^+ - n^+$ Junctions

4.4 Conclusions

A reduction of three orders of magnitude in forward bias tunneling current densities of RTCVD fabricated Si/Si and Si/SiGe junctions compared to ion implanted results is observed. These results demonstrate the high quality of the epitaxial interface, i.e. lower interface states densities compared to ion-implanted junctions. Low tunneling currents allow higher limits to transistor base and emitter dopings which imply higher gains, reduced base resistances and higher Early voltages of scaled devices. The results imply an upper limit of doping at the base-emitter interface of $1 \times 10^{19} \text{ cm}^{-3}$ before a substantial degradation of base current in Si/Si$_{1-x}$Ge$_x$ HBT's.
4. Tunneling Current in p⁺ – n⁺ Junctions

a)

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</tr>
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<td>12</td>
<td>Si/SiGe</td>
</tr>
<tr>
<td>468</td>
<td>1.5</td>
<td>-</td>
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<tr>
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<td>1.5</td>
<td>-</td>
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</table>

b)

<table>
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<td>(10ppm in H₂)</td>
<td></td>
</tr>
<tr>
<td>436</td>
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<td></td>
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Table 4.1: Summary of p⁺-n⁺ diodes: a) doping, b) growth parameters
Chapter 5

Lateral Hole and Vertical Electron Currents in Si$_{1-x}$Ge$_x$ Bases

5.1 Introduction

Although high performance Si/Si$_{1-x}$Ge$_x$/Si bipolar devices have been demonstrated, experimental data for even DC modeling of these devices is still lacking. In silicon, it is well known that the heavy doping in the emitter of bipolar transistors causes bandgap narrowing that affects minority carrier transport, namely, the narrower gap in the emitter causes an exponential decrease in collector current (an opposite effect to HBT action). For that reason, heavy doping effects in silicon, particularly in n-type material, have been extensively studied [84, 85, 88, 89].

In Si/Si$_{1-x}$Ge$_x$/Si HBT's, the Si$_{1-x}$Ge$_x$ base is generally heavily doped. The effects of heavy base doping on vertical electron and lateral hole currents have not been substantially experimentally measured, although heavy base doping is often employed in the design of narrow-base devices. Vertical minority carrier transport, crucial for accurate modeling of collector current, is affected by heavy-doping-induced bandgap narrowing while lateral hole current, which is important for base sheet resistance, is affected by hole drift mobility. One needs to study both the effects of Ge and the doping to understand and accurately predict the performance of Si/Si$_{1-x}$Ge$_x$/Si HBT's.
5. Lateral Hole and Vertical Electron Currents in $\text{Si}_{1-x}\text{Ge}_x$ Bases

In this chapter we present a set of comprehensive measurements of lateral hole current and vertical electron current across the strained $\text{Si}_{1-x}\text{Ge}_x$ base of an npn HBT in a wide range of base dopings and Ge concentrations. Based on room temperature measurements, we have extracted the effective bandgap for electron transport. We have also developed an empirical model for the collector current enhancement with respect to all-Si devices vs. base sheet resistance.

5.2 Device fabrication

For this study, we fabricated $\text{Si}/\text{Si}_{1-x}\text{Ge}_x/\text{Si}$ HBT's with flat Ge and B profiles in the base grown by Rapid Thermal Chemical Vapor Deposition (RTCVD). $\text{Si}_{1-x}\text{Ge}_x$ layers were grown at 625°C, while Si emitters were grown at 800°C for 7.5 minutes. Base dopings ranged from $10^{18}\text{cm}^{-3}$ to $10^{20}\text{cm}^{-3}$ and Ge concentrations ranged from 0% to 27%. Base widths varied from 300Å to 2000Å. The devices with more Ge in the base had narrower bases to avoid strain relaxation. The Ge concentrations were measured by x-ray diffraction. The Ge fraction was measured by the shift of the 400 peak (Cu Kα radiation line) using: $x = 0.178 \times \Delta(2\theta)$. The estimated error in $x$ is ±1%. Undoped SiGe base-emitter and base-collector layers, 50Å to 200Å thick were introduced to avoid parasitic barriers due to boron outdiffusion during the emitter growth (see chapter 2). SIMS measurements confirmed flat profiles, base dopings and widths, and that the B-doping was contained within the SiGe layer (Fig. 5.1). The device structure is shown in Fig. 5.2. Van der Pauw patterns for base resistance measurements were made on each sample in addition to transistors.

A simple double mesa wet-etch process without any thermal cycles over 400°C was used to prevent any possibility of parasitic barriers due to the thermal diffusion. No emitter implants were used since these can cause anomalous base dopant diffusion in $\text{Si}_{1-x}\text{Ge}_x$ HBT's for even moderate temperatures [90] and thus cause parasitic
Figure 5.1: A typical SIMS profile of a device used in this study. Si and Ge are in arbitrary units. B was contained within the SiGe layer even for the heaviest doped devices.
n-Si

Van der Pauw

Transistor

Figure 5.2: A typical device structure used in this study. Van der Pauw patterns were fabricated next to transistor devices.

barriers. A selective wet etch [91] was used to remove the emitter for contacting the base layer. The highest temperature step in the whole process was during the emitter growth. We have done experiments prior to this study to confirm that the Si$_{1-x}$Ge$_x$ layers were fully strained and no barrier formation occurred during the emitter growth (also confirmed by SIMS).

The emitter area of transistors ranged from 20 \times 20 \mu m^2 to 100 \times 100 \mu m^2. No significant perimeter effects in the collector current measurements were observed.

5.3 Majority carrier properties

Lateral hole mobility in p-type heavily doped Si$_{1-x}$Ge$_x$ is of great importance for accurate modeling of base sheet resistance. The mobility important for base sheet resistance in equation 2.6 is the low field drift mobility. However, the most often measured mobility is the one measured by Hall measurements, i.e. Hall mobility. Drift and Hall mobilities reflect the band structure and scattering mechanism in different ways. They are the same in case of parabolic or spherical energy bands and energy independent carrier scattering times. This is not the case, however, in heavily doped, strained Si$_{1-x}$Ge$_x$. The ratio of Hall and drift mobility is usually defined as
the Hall scattering factor \( r_H = \frac{\mu_{p,\text{Hall}}}{\mu_{p,\text{drift}}} \).

The strain affects the band structure in Si\(_{1-x}\)Ge\(_x\) alloys. The degeneracy of conduction and valence bands is lifted, moving four conduction band minima in the growth plane down with respect to the other two, and splitting heavy and light hole bands with the heavy hole band lying higher. Because of strain-induced changes in the energy bands of Si\(_{1-x}\)Ge\(_x\) alloys, a reduction in hole effective mass compared to bulk Si is expected [92]. This would tend to cause a higher drift mobility [93, 94]. The effect is expected to be more pronounced in the direction perpendicular to the growth plane. On the other hand, the presence of alloy scattering would tend to reduce the hole mobility. Some experimental evidence exists to support an enhancement in hole drift mobility with increasing Ge concentration at a single doping level [95]. In this work we measured hole Hall mobilities, sheet resistivities, drift mobilities and Hall scattering factors over a wide range of dopings (10\(^{18}\) \(-\) 10\(^{20}\)cm\(^{-3}\)) and Ge concentrations (0-27\%).

Fig. 5.3.a shows the measured Hall mobility (\(\mu_{p,\text{Hall}}\)) of holes at room temperature as a function of base doping. Different symbols represent different Ge concentrations (\(x\)). A decrease in the Hall mobility with increasing doping is obvious, as expected due to the increase in ionized impurity scattering. However, for similar doping levels, Hall mobilities decrease with the increasing Ge concentration. This is clearly shown in Fig. 5.3.b where the Hall mobility is plotted vs. Ge concentration for devices with similar doping levels.

The measurement of drift mobility (\(\mu_{p,\text{drift}}\)) and Hall scattering factor requires an independent measurement of carrier concentration in the base, in addition to Hall measurements. The integrated hole concentration was obtained from SIMS profiles, assuming full dopant activation. The SIMS results were calibrated by implanted standards into similar Si\(_{1-x}\)Ge\(_x\) layers. The results were also corrected for the expected effects of base-emitter and base-collector space-charge regions. The full activation of
5. Lateral Hole and Vertical Electron Currents in $\text{Si}_{1-x}\text{Ge}_x$ Bases

Figure 5.3: a) Hole lateral Hall mobility as a function of base doping for various Ge concentrations, b) Hole lateral Hall mobility as a function of Ge concentration for different doping levels.
B atoms is a reasonable assumption, since the emitters were grown at 800°C for 7.5 minutes after the in-situ doped Si$_{1-x}$Ge$_x$ base layers. The accuracy of the extracted values for Hall scattering factor and drift mobility is expected to be ±20%. By comparing the measured integrated hole concentration in the base by Hall measurements to those measured by SIMS, we extracted the Hall scattering factor. Fig. 5.4 shows the Hall scattering factor as a function of x. It is obvious that the Hall scattering factor decreases with increasing Ge content and for x ≥ 0.1 is actually less than unity.

No clear doping dependence of Hall scattering factor was observed. Note that if the hole concentrations were lower than the chemical boron concentrations obtained by SIMS (due to incomplete dopant activation), the resulting Hall scattering factor would be even lower. A similar trend of decreasing Hall scattering factor with increasing Ge concentration was also observed by McGregor et al. [95]. This behaviour is not yet well understood. The difference between Hall and drift mobility depends on the
detailed structure of the valence bands and hole scattering mechanisms which, to the knowledge of the authors, has not been addressed in Si$_{1-x}$Ge$_x$ strained alloys.

Fig. 5.5.a shows drift mobility as a function of base doping for different Ge concentrations. No clear dependence of drift mobility on Ge concentration was observed, as illustrated in Fig. 5.5.b. Although at dopings of $5 - 7 \times 10^{18}\text{cm}^{-3}$ a slight increase with increasing Ge content was noticed, consistent with the results of ref. [95], at high doping levels ($1 - 2 \times 10^{20}\text{cm}^{-3}$) no dependence on Ge concentration was observed. For subsequent modeling purposes, a best fit to experimental data is given by:

$$
\mu_{\text{P_{eff}}} = 20 + \frac{350}{1 + \left(\frac{N_A}{10^{17}\text{cm}^{-3}}\right)^{0.5}} \quad (5.1)
$$

This is plotted as a dashed line in Fig. 5.5. Measurement of hole drift mobility in a wide range of doping and Ge concentrations enables the prediction of base sheet resistance for an arbitrary structure.

### 5.4 Effective bandgap measurements and model

The effect of bandgap narrowing in heavily doped Si, relevant for electrical device performance, is often modeled as an increase in intrinsic effective minority carrier concentration [96, 97]. For a p-type material this would be:

$$
n_{i,\text{eff}}^2 = n_{i,\text{o}}^2 e^{\frac{\Delta E_{G,\text{eff}}}{kT}} \quad (5.2)
$$

where $n_{i,\text{eff}}$ is the effective intrinsic carrier concentration, $n_{i,\text{o}}$ is the true intrinsic carrier concentration and $\Delta E_{G,\text{eff}}$ is the effective (apparent) bandgap narrowing. We have extended this approach to HBT’s, where $\Delta E_{G,\text{eff}}$ includes bandgap narrowing due to Ge in the base as well as heavy doping.

It is well known that the collector saturation current density of an HBT with flat Ge and doping profiles without parasitic conduction band barriers or spikes due to
Figure 5.5: a) Drift mobility as a function of base doping for various Ge concentrations. The line is the fit to data, b) Drift mobility as a function of Ge concentrations for two doping levels.
conduction band offsets in the base can be modeled as:

\[ J_{co} = \frac{qD_nN_cN_v}{G_B} \left( e^{-\frac{\Delta E_{G,eff}}{k_BT}} \right) \]

(5.3)

where \( D_n \) is the minority carrier diffusion coefficient, \( N_c \) and \( N_v \) are conduction and valence band densities of states, \( G_B \) is the Gummel number in the Si\(_{1-x}\)Ge\(_x\) base, and \( E_{G,eff} \) is the effective bandgap for minority carrier concentration in the base. The effective bandgap is determined by the Ge concentration in Si\(_{1-x}\)Ge\(_x\), but narrowing due to heavy doping, observed in Si [85] and SiGe [98], should also be taken into account. The equation 5.3 can be rewritten as follows:

\[ J_{co} = \frac{qD_{n,SI}N_cN_v}{G_{B,SI}} \left( \frac{N_cN_v}{N_n} \right) \left( e^{-\frac{\Delta E_{G,eff}}{k_BT}} \right) \]

(5.4)

where \( \Delta E_{G,eff} \) is the effective bandgap reduction with respect to intrinsic Si. The ratio \( \left( N_cN_v \right)_{SI} \left/ \left( N_cN_v \right)_{Si} \right. \) represents the reduction in densities of states due to strain-induced splitting of the bands in Si\(_{1-x}\)Ge\(_x\), and all heavy doping effects are included in \( \Delta E_{G,eff} \).

Based on equation 5.4 there are two ways in which \( \Delta E_{G,eff} \) may be found. The first possibility is to compare \( J_{co} \) of the HBT to that of a similar all-Si device as a function of temperature [14, 99, 100, 18]. If one assumes a similar temperature dependence of mobility, densities of states and bandgap in the Si\(_{1-x}\)Ge\(_x\) as in Si, one can extract a \( \Delta E_{G,eff} \) from the temperature dependence of the ratio of \( J_{co} \) in the two devices. This method has an advantage that no knowledge of electron diffusion coefficient \( D_n \) or base doping level is required. However, if one uses a lightly doped Si sample as a reference, one makes an implicit error because of the known difference in the temperature dependence of \( D_n \) in p-type Si at different doping levels [101]. For example, from room temperature down to 200K, the ratio of \( D_n \) in p-type Si doped \( \sim 5 \times 10^{18} \) cm\(^{-3}\) to that doped \( 6 \times 10^{19} \) cm\(^{-3}\) changes from 1.1 to 0.3 [85, 101]. This could introduce an error of \( \sim 65 \) meV in \( \Delta E_{G,eff} \) if it were extracted from a fit of the
ratio of \( J_{C0} \)'s over this same temperature range. This might be overcome if one had all Si transistors with the same base dopings as all HBT's, but this would not give an absolute number for the bandgap reduction due to heavy doping. Furthermore, because of alloy scattering, one might expect a different temperature dependence of \( D_n \) in Si and SiGe of similar dopings. Finally, while the \( \Delta E_{G,\text{eff}} \) extracted by this method will by definition accurately model the temperature dependence of the collector current, it may not be a good predictor of the absolute value of room temperature collector current, which is more important than its temperature scaling for most modeling applications.

Therefore in this study we have chosen to make measurements of \( G_B \) and to make reasonable assumptions for \( D_n \) and the densities of states ratio, so that an absolute value of \( \Delta E_{G,\text{eff}} \) (compared to undoped Si as represented by \( n_{\text{lo}}^2 \)) can be extracted.

Fig. 5.6 shows a typical Gummel plot of a transistor used in this study. The collector current is ideal over several orders of magnitude, and the negligible effect of the reverse collector bias indicates no parasitic barriers due to boron outdiffusion, even for very heavy dopings in the base \( (10^{20}\text{cm}^{-3}) \), as confirmed by SIMS. Measurements on different area devices showed negligible perimeter effects.

Since both conduction and valence bands split in strained \( \text{Si}_{1-x}\text{Ge}_x \) the effective densities of states will be lower than in Si. To take the reduction of densities of states into account, we used the model of Prinz et al.[48]. This model assumes a rigid splitting of both the conduction and valence band degeneracies due to uniaxial strain. One can then calculate the densities of states reduction factor \( (N_CN_V)_{\text{SiGe}}/(N_CN_V)_{\text{Si}} \) as a function of Ge concentration and temperature. For the Ge concentrations of interest (7-27\%) the reduction factor is in the range of 0.6-0.3 at room temperature. A more rigorous calculation using the band structure of [102] would give even lower value of \( N_V \) in strained \( \text{Si}_{1-x}\text{Ge}_x \) \( (\sim 0.3 \text{ for } x=0.2) \)[94].

To model the minority carrier mobility in the base, we used the Si model of
Figure 5.6: Typical Gummel plot of an HBT used in this study. Ge concentration in this device was 23% with the base doping of $3 \times 10^{18}$ cm$^{-3}$. 
Swirhun et al. [85] for electron mobilities as a function of B-doping. This is a reasonable approximation since calculations by Kay and Tang [103] of minority electron mobility in strained Si$_{1-x}$Ge$_x$ alloys predict at most an enhancement of 20% over Si values in the doping range of interest. Note also that we observed no clear evidence of significant enhancement of lateral hole drift mobilities with increased Ge concentrations, especially at high doping levels. The base Gummel number G$_B$ was measured directly by SIMS on the same wafer on which the devices were made. The Gummel number was also obtained by the lateral base transport measurements. The agreement with that found by SIMS was obtained within the uncertainty of 30% due to the uncertainty in the Hall scattering factor. On devices where no SIMS data was available, the Gummel number obtained by Hall measurements was used, corrected by the Hall scattering factor of Fig. 5.4. Finally, for $n_{i,0, Si}$ the accepted value of $1 \times 10^{20}$ cm$^{-3}$ at 295K was used. The estimated total uncertainty on the prefactor in equation (3) (combined uncertainty of D$_n$, G$_B$, and the densities of states ratio) was a factor of 2. This corresponds to an uncertainty of 17 meV in the extracted $\Delta E_{G, eff}$. The summary of the samples and the most relevant measured parameters is given in Table 5.1.

Using this method, Fig. 5.7 shows the extracted effective bandgap narrowing at room temperature as a function of Ge concentration for different doping levels. For the devices with similar dopings, the linear dependence on Ge concentration is obvious. Fitting the data at the same doping level gives a bandgap offset with respect to Si of $\sim 7$meV/1%Ge. Assuming that this linear dependence on Ge concentration is independent of doping, we have separated the two effects contributing to bandgap reduction with respect to undoped Si: bandgap reduction due to Ge ($\Delta E_{G, Ge}$) and bandgap narrowing due to heavy doping effects ($\Delta E_{G, dop}$).

$$\Delta E_{G, eff} = \Delta E_{G, Ge} + \Delta E_{G, dop}$$ (5.5)
5. Lateral Hole and Vertical Electron Currents in Si$_{1-x}$Ge$_x$ Bases

Assuming a $\Delta E_{G,dop}$ of the form:

$$\Delta E_{G,dop} = A + B \times \log\left(\frac{N_A}{10^{18}\text{cm}^{-3}}\right)$$  \hspace{1cm} (5.6)

and a linear dependence of $\Delta E_{G,Ge}$ on $x$ as $Cx$, a three-parameter best fit to our data was found to be:

$$\Delta E_{G,eff} = 28.6 + 27.4 \times \log\left(\frac{N_A}{10^{18}\text{cm}^{-3}}\right) + 688 \times x \hspace{1cm} \text{(meV)}$$  \hspace{1cm} (5.7)

where $N_A$ is the base doping and $x$ the Ge concentration. The first two terms represent bandgap narrowing due to doping and the last term is the Ge contribution. $\Delta E_{G,eff}$ is not the measure of the actual bandgap reduction, but the effective (apparent) bandgap reduction, relevant for minority carrier concentration and thus electron transport across the Si$_{1-x}$Ge$_x$ base. The apparent bandgap is larger than the true bandgap due to valence band filling in the degenerately doped semiconductor and hence, the effects of Fermi-Dirac statistics [104]. The effective bandgap reduction is a useful parameter to model the collector current of Si/Si$_{1-x}$Ge$_x$/Si HBT's and predict the enhancement over Si-base devices.

Experimental values for $\Delta E_{G,dop}$ for Si$_{1-x}$Ge$_x$ are obtained by subtracting the germanium contribution (688x meV) from the measured $\Delta E_{G,eff}$. These values are plotted in Fig. 5.8 vs. base doping. This is the first time that such data has been collected for such a wide range of dopings and Ge concentrations in Si/Si$_{1-x}$Ge$_x$/Si HBT's. Also plotted are previously reported results by Swirhun et al.[85] and model by Klaassen et al.[89] for apparent bandgap narrowing in p-type Si. The apparent bandgap narrowing clearly increases with increased doping, as expected. No clear Ge dependence is observed after the linear dependence has been subtracted. The bandgap narrowing of 27meV/decade agrees well with the 25-33meV narrowing at various Ge concentrations with the doping increase from $5 \times 10^{17}\text{cm}^{-3}$ to $5 \times 10^{18}\text{cm}^{-3}$, obtained from temperature dependent measurements by Poortmans et al.[98].
Figure 5.7: Effective bandgap reduction with respect to intrinsic Si vs. Ge concentration

- $1 - 7 \times 10^{18}\text{cm}^{-3}$
- $1 - 6 \times 10^{19}\text{cm}^{-3}$
- $1 - 2.5 \times 10^{20}\text{cm}^{-3}$

slope: 7meV/1%Ge
Figure 5.8: Apparent bandgap narrowing vs. base doping after linear dependence of the bandgap reduction on Ge content has been subtracted.
Figure 5.9: Apparent bandgap narrowing vs. base doping after linear dependence of the bandgap reduction on Ge content has been subtracted compared with data from literature.

Plotted in Fig. 5.9 are data points for $\Delta E_{G,dop}$ for other SiGe HBT's reported in the literature [19, 14, 18, 24, 90], along with our data of Fig. 5.8 and the model for $\Delta E_{G,dop}$. $\Delta E_{G,eff}$, as defined in this work, was not directly given in these papers, but adequate information on base doping, base-width, collector current, etc. was given so that $\Delta E_{G,eff}$ could be calculated. $\Delta E_{G,dop}$ was then found after subtracting the linear dependence on Ge, as described earlier. In general the data of the other work also lie near our best fit for $\Delta E_{G,eff}$. It is interesting to note that nearly all of the data points which fall substantially below the best fit line are from devices which were fabricated using an implanted emitter process, which is known to give rise to excess base dopant diffusion (and possible parasitic barrier formation resulting in smaller $\Delta E_{G,eff}$) [90].

Note that our results for $\Delta E_{G,dop}$ are consistently lower than those found in Si (as
represented by the work of Swirhun [85] and Klaassen [89]), although calculations by Jain et al. [105] predict $\Delta E_{G,dop}$ to be slightly higher in SiGe than in Si, and strain-dependent. A possible explanation for smaller apparent bandgap narrowing compared to Si lies in the fact that at the same doping level, due to the band splitting and thus, reduced densities of states, the Fermi level in degenerately doped $Si_{1-x}Ge_x$ lies higher in the valence bands, and thus contributes more to the apparent bandgap reduction. To relate the apparent bandgap narrowing to the true bandgap reduction ($\Delta E_{G,true}$) one needs to know the position of the Fermi level in the degenerately doped material and take into account the effect of degenerate statistics (Fermi-Dirac instead of Boltzmann), as illustrated in Fig. 5.10. The hole concentration (doping) is related to the Fermi level ($E_F$) by [86]:

$$p = N_A = N_V \sqrt{\frac{2}{\pi}} F_{1/2} \left( \frac{E_V - E_F}{k_B T} \right)$$

(5.8)

where $F_{1/2}(E_F/k_BT)$ is the Fermi-Dirac integral. Fig. 5.11 shows the calculated position of the Fermi level with respect to the valence band edge as a function of base doping for Si and $Si_{0.8}Ge_{0.2}$ using equation 5.8 and the model of Prinz et al. [48] for the effective valence band density of states in $Si_{1-x}Ge_x$. Note that the position of the Fermi level starts to diverge from the straight line in the case of $Si_{0.8}Ge_{0.2}$ at a lower doping level, and diverges much faster with increasing doping, thus having a bigger effect on $\Delta E_{G,eff}$ than in Si at the same doping level. Possin et al. [104] have the first modeled the apparent bandgap narrowing as the sum of the true bandgap narrowing ($\Delta E_{G,true}$) and the negative term representing the Fermi-Dirac ($\Delta E_{G,FD}$) correction given as:

$$\Delta E_{G,eff} = \Delta E_{G,true} + \Delta E_{G,FD}$$

(5.9)

$\Delta E_{G,FD}$ is always negative and it is given by:

$$\Delta E_{G,FD} = \ln \left[ e^{\frac{E_V - E_F}{k_B T}} F_{1/2} \left( \frac{E_V - E_F}{k_B T} \right) \right] = -(E_v - E_F) + k_BT \ln \frac{N_A}{N_V}$$

(5.10)
Figure 5.10: Qualitative band diagram illustrating the difference between the true and the effective bandgap
Figure 5.11: Position of the Fermi level with respect to the valence band edge for Si and Si$_{1-x}$Ge$_x$. 
Fig. 5.12 shows calculated values for $\Delta E_{G,FD}$ at room temperature as a function of doping for $x = 0$, 10 and 20% using equation 5.10. We have applied the $\Delta E_{G,FD}$ to our Si_{1-x}Ge_x data of Fig. 5.7 and subtracted the linear Ge dependence ($\Delta E_{G,Ge} \sim 7\text{meV/1\%}$) to extract the true Si_{1-x}Ge_x bandgap reduction. The results are plotted in Fig. 5.13. Also shown in the figure are the theoretical calculation for the true bandgap narrowing in p-Si by Jain and Roulston [105] (solid line) and room temperature Si-data of Wagner [106] measured by photoluminescence. The $\Delta E_{G,dop,true}$ agrees fairly well with the Si data at lower dopings, but at heavy doping levels the Si_{1-x}Ge_x data lies higher. There is no clear Ge dependence on $\Delta E_{G,dop,true}$, however. If the carrier concentration effective mass of ref. [92] were used, which would result in even bigger $\Delta E_{G,FD}$, the data points would shift to even higher values of $\Delta E_{G,dop,true}$.
Figure 5.13: The heavy-doping contribution to the true bandgap reduction in strained $\text{Si}_{1-x}\text{Ge}_x$ calculated from the measured $\Delta E_{G,\text{eff}}$ as: $\Delta E_{G,dop,\text{true}} = \Delta E_{G,dop} - \Delta E_{G,FD}$. Also shown for comparison are the Si data points of Wagner and the theoretical calculation for p-Si of Jain and Roulston (solid line).
at high doping levels and higher Ge concentrations. On the other hand, the observed Fermi energy in p-Si is less than predicted by the conventional density of states equation (5.8) [107]. If similar behaviour were the case in Si$_{1-x}$Ge$_x$, this would result in overestimated $\Delta E_{G,dop,true}$. Although some uncertainty in the absolute value of $\Delta E_{G,dop,true}$ remains, the Fermi level in strained Si$_{1-x}$Ge$_x$ clearly lies higher than in Si for the same doping level resulting in stronger effects of degenerate statistics. Thus, the weaker doping dependence and lower values compared to Si data of the apparent $\Delta E_{G,dop}$ are attributed to the larger effect of $\Delta E_{G,FD}$ in Si$_{1-x}$Ge$_x$ than in Si.

5.5 Collector current vs. base resistance model

The two important parameters for the DC design of Si$_{1-x}$Ge$_x$ HBT's is the base sheet resistance and the collector current enhancement with respect to Si. The base sheet resistance is important for high-speed application of Si$_{1-x}$Ge$_x$ HBT's and is often more easier measured (and more relevant) than the actual doping in the base or the integrated hole concentration. The effective bandgap reduction determines the collector current enhancement factor over the similarly doped all-Si device. By using $R_*= (q\mu_p G_B)^{-1}$ one can rewrite equation 5.4 to model the collector current as a function of these two parameters:

$$J_{co} = q^2 \frac{(N_C N_V)_{SiGe}}{(N_C N_V)_{Si}} n_{io,Si}^2 D_n \mu_p R_{B,\text{sheet}} e^{\frac{\Delta E_{G,eff}}{kT}}$$

(5.11)

where $\mu_p$ and $D_n$ are the lateral drift hole mobility and vertical electron diffusion coefficient in p$^+$-base, respectively. Equation 5.11 shows a clear trade-off between collector current (gain) and base sheet resistance. This is summarized in Fig. 5.14. The relative collector current with respect to Si is plotted as a function of base sheet resistance for various Ge concentrations. A relative collector current factor of one is defined for Si at a base sheet resistance of 1k$\Omega$/sq. The lines are the model calculations
5. Lateral Hole and Vertical Electron Currents in Si$_{1-x}$Ge$_x$ Bases

Figure 5.14: Relative collector current vs. base sheet resistance. The lines correspond to the model, the points are the data assuming base widths of 500Å, hole drift mobilities given by equation 5.1, bandgap reduction by equation 5.7, strain-induced correction for densities of states given by [48] and electron mobility by [85]. The points are measured data in our HBT's scaled to 500Å base-widths. Note especially the effect of the bandgap narrowing due to heavy base doping which has a more significant effect than the lateral and vertical mobility reduction at heavy dopings. The bandgap narrowing causes curves not to be linear, and limits the reduction in collector current at low base resistances.

5.6 Summary

This chapter provides a comprehensive study of majority carrier properties in heavily B-doped strained Si$_{1-x}$Ge$_x$ layers as well as collector currents of HBT's in the
5. Lateral Hole and Vertical Electron Currents in Si$_{1-x}$Ge$_x$ Bases

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<th>Sample number</th>
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<th>$G_B$ -SIMS ($10^{14}$cm$^{-2}$)</th>
<th>$G_B$ -Hall ($10^{14}$cm$^{-2}$)</th>
<th>$N_A$ ($10^{19}$cm$^{-3}$)</th>
<th>doped $w_B$ (Å)</th>
<th>$R_{B,sheet}$ (kΩ/sq.)</th>
<th>$J_{co}$ (nA/cm$^2$)</th>
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Table 5.1: Summary of HBT samples and relevant parameters ($G_B$ -SIMS is the raw data uncorrected for depletion region effects, $G_B$ -Hall is calculated assuming $r_H = 1$)

A wide range of dopings and Ge concentrations for the first time [108]. The hole Hall mobility decreases with increasing Ge concentration at a fixed doping level, because the Hall scattering factor decreases as Ge is added. The lateral hole drift mobility remains approximately constant as Ge is added, with perhaps a slight increase at low doping levels. The apparent bandgap narrowing in p-type strained Si$_{1-x}$Ge$_x$ was measured for the first time over a wide range of doping and Ge levels. The dependence of the narrowing on Ge was independent of doping, and the heavy doping contribution to the effective bandgap narrowing is found to be independent of Ge concentration but slightly lower than that obtained for Si at the same doping level,
attributed to the Fermi-Dirac statistics effect. Finally, a trade-off between the collector current enhancement and base sheet resistance is presented for DC modeling of Si$_{1-x}$Ge$_x$ HBT's. The bandgap narrowing at heavy doping levels (low base sheet resistances) has a larger impact than that of reduced mobility at high doping levels.
Chapter 6

Minority Carrier Properties in $\text{Si}_{1-x}\text{Ge}_x$

6.1 Introduction

Bipolar transistors rely on minority carrier transport across the device. This is why accurate modeling of minority carrier transport deserves a lot of attention. Important parameters to characterize it are minority carrier mobility ($\mu_n$ in p-type material), minority carrier lifetime ($\tau_n$), and minority carrier diffusion length ($L_n$), which are related by:

$$L_n = \sqrt{D_n \tau_n}$$

(6.1)

where $D_n$ is the diffusion coefficient ($D_n = \mu_n \times k_B T / q$). The collector current density of a bipolar transistor in forward active mode is given by:

$$J_c = \frac{q D_n n_i^2}{N_A L_n \sinh(w_B/L_n)} e^{\frac{qV_B}{k_B T}}$$

(6.2)

In case of narrow bases ($w_B << L_n$) equation 6.2 simplifies to 5.3 for DC collector current. In the previous chapter, we have measured $n_i^2$ (i.e. $E_Q$) in doped $\text{Si}_{1-x}\text{Ge}_x$ assuming that $D_n$ is the same as in silicon (given by [84]). Although this assumption might be reasonable considering no significant Ge-dependence on majority hole mobility in heavily doped HBT bases, the accurate values of minority carrier mobility still need to be determined in strained $\text{Si}_{1-x}\text{Ge}_x$ alloys.
It has been experimentally observed that the minority carrier mobility in heavily doped silicon is larger than majority carrier mobility \([85, 84]\). The difference between majority and minority mobilities are not surprising, since apart from heavy doping effects on the bandgap structure, the dominant impurities for electron scattering become acceptors instead of donors, i.e. majority carriers are holes instead of electrons. Both electron-hole and electron-electron scattering need to be taken into account. The temperature dependence of minority carrier mobility is also very different from the majority \([101]\). In case of strained Si\(_{1-x}\)Ge\(_x\) alloys, the minority carrier mobility is also expected to be affected by strain and alloy scattering.

One could independently determine the minority carrier diffusion coefficient in strained Si\(_{1-x}\)Ge\(_x\) by measuring both the lifetime and minority carrier diffusion length. In this chapter, we report the design of the lateral device structure for diffusion length and lifetime measurements and diffusion length results for strained Si\(_{1-x}\)Ge\(_x\) layers in the p-type doping range of \(2 \times 10^{17} \text{ cm}^{-3}\) to \(4 \times 10^{18} \text{ cm}^{-3}\).

### 6.2 Methods to measure minority carrier diffusion length and mobility

In silicon, many types of device structures have been used over the years by various authors to extract minority carrier properties. A critical review of measurements previously reported is included in the work of del Alamo \([96]\) and Swirhun \([97]\). Since collector current in a bipolar transistor is a clean monitor of minority carriers through the base and it is ideal with respect to base-emitter voltage, del Alamo \([96]\) and Swirhun \([97]\) have reported a comprehensive set of diffusion length measurements on lateral bipolar transistors for n and p-type Si, respectively (the method first used by Wieder \([109]\)). In case of wide-base bipolar transistor (\(w_B \gg L_n\)) from equation
6. Minority Carrier Properties in \( \text{Si}_{1-x}\text{Ge}_x \)

6.2 Collector current becomes:

\[
I_c = A \frac{2qD n i^2}{N_A L_n} e^{-\frac{v_B}{v_{th}}} e^{\frac{v}{v_{th}}} \tag{6.3}
\]

In case of lateral devices \( A \) is the collecting area which includes two-dimensional effects. The lateral devices were obtained by implantation of emitter and collector into the base material. From the collector current measurements on devices with various basewidths, the diffusion length was determined by fitting \( I_c \) vs. \( w_B \).

Minority carrier mobility cannot be extracted just from DC measurements. To measure minority carrier mobility a time-dependent technique needs to be used. For example, if one independently measured lifetime, the mobility could be extracted by combining the lifetime with the diffusion length measurements. The lifetime at heavy doping levels is expected to be a fundamental property of the material due to recombination dominated by Auger processes. No data on minority carrier lifetime is available for \( \text{Si}_{1-x}\text{Ge}_x \) at present.

Lifetime can be measured by decay of photoluminescence radiation of electron-hole pairs after excitation by a short laser pulse \([110, 111, 85]\). Since band-edge photoluminescence has been observed in \( \text{Si}_{1-x}\text{Ge}_x \) alloys \([65]\) one could essentially measure lifetime. However, photoluminescence from \( \text{Si}_{1-x}\text{Ge}_x \) quantum wells has only been observed at low temperatures which restricts lifetime measurements to below room temperature. Minority carrier lifetime could also be measured as a decay of photoexcited carriers, as proposed by Stevenson and Keyes \([112]\). The excess carrier generated by light pulses cause a momentary increase in the conductivity. The decay of that conductivity is a measure of lifetime. Another method to measure lifetime is from AC diffusion length measurements, as demonstrated by Dziewior and Silber \([113]\), since the diffusion length measured at frequency \( \omega \) is related to the DC \( (L_0) \) value by:

\[
L(\omega) = \frac{L_0}{\sqrt{1 + j\omega \tau}} \tag{6.4}
\]
Misiakos et al. [114] have proposed a method for simultaneous measurement of diffusion coefficient, lifetime and diffusion length based on lateral collection of photogenerated carriers by a semi-infinite junction by DC measurements and transient response in the frequency domain.

To our knowledge, the only reported measurement of the electron diffusion coefficient in Si$_{1-x}$Ge$_x$ by King et. al. [14] was based on DC measurements on vertical HBT collector current. He was forced to make the assumption of no differences in densities of states between Si and strained Si$_{1-x}$Ge$_x$ and that minority carrier diffusion coefficients in Si and Si$_{1-x}$Ge$_x$ have the same temperature dependence. Furthermore, high values of oxygen contamination ($1 \times 10^{20}$ cm$^{-3}$) were present in these Si$_{1-x}$Ge$_x$ layers.

We have designed a lateral device structure for the diffusion length measurements. Although one cannot provide a bulk strained Si$_{1-x}$Ge$_x$ material, one can optimize layer structure such that the lateral minority carrier current transport is dominated by the transport through a thin Si$_{1-x}$Ge$_x$ layer. This is possible due to conduction band offset between p$^+$-Si and p$^+$-Si$_{1-x}$Ge$_x$. However, special care needs to be taken to prevent parallel Si transport, as well as loss of carriers due to surface recombination. The same structure could be used for lifetime measurements by monitoring the decay of photoconductivity [112] or, at low temperatures, by measuring photoluminescence decay. The following sections discuss the proposed device structure and the design details, as well as initial diffusion length measurements.

6.3 Structure optimization for measurements of minority carrier parameters in strained SiGe alloys

Due to strain relaxation constrains (see chapter 2) Si$_{1-x}$Ge$_x$ material can only be fabricated in thin layers, on the order of 100–1000Å. That makes it impossible to
design vertical "long-base" devices, so "long-base" device structures are limited to lateral transport. An issue that needs to be solved in lateral devices is the confinement of minority carriers within the thin Si$_{1-x}$Ge$_x$ layer. However, in case of p-Si/p-Si$_{1-x}$Ge$_x$/p-Si heterostructures, since the bandgap of strained Si$_{1-x}$Ge$_x$ is smaller than silicon bandgap, it is reasonable to assume that most of electrons are going to be confined within the Si$_{1-x}$Ge$_x$ layer. Such heterostructures were optimized using 2D device simulation program (MEDICI) by simulating lateral bipolar transistors for diffusion length measurements. The structure is shown in Fig. 6.1. The emitter and collector would be fabricated by ion implantation and annealing. The distance between the emitter and collector implant determines the basewidth $w_B$. Fig. 6.2
shows the simulated band diagram of a p⁺-Si/p⁺-Si₀.₈Ge₀.₂/p⁺-Si heterostructure. For ~ 20% germanium in the Si₁₋ₓGeₓ layer the conduction band difference is ~ 140meV between the Si and Si₁₋ₓGeₓ.

In lateral bipolar transistors, the collector current is inversely proportional to \( \exp(w_B/L_n) \) (equation 6.3), so the slope of the measured collector current, on a logarithmic scale, vs. \( w_B \) gives the diffusion length. To first order the ratio of lateral currents in Si₁₋ₓGeₓ and Si is given by:

\[
\frac{I_c(SiGe)}{I_c(Si)} \approx \frac{A(SiGe)}{A(Si)} \frac{N_A(Si)}{N_A(SiGe)} \frac{N_C N_V(SiGe)}{N_C N_V(Si)} e^{\frac{\Delta E_F}{k_B T}}
\]

The thicker the Si₁₋ₓGeₓ layer, more current will flow through Si₁₋ₓGeₓ. The thickness of the Si₁₋ₓGeₓ layer is limited by the critical thickness. The implants need to be shallow to minimize the collecting area in silicon. The higher the doping in
surrounding Si layers the better is the current ratio (i.e. less current in Si), until the doping level is reached to start causing significant bandgap narrowing or leakage currents in p⁺–n⁺ junctions. The losses of minority carriers to the substrate or to the surface also need to be taken into account. The doping and the thickness of the bottom Si layer were optimized for negligible substrate effects. For p-type Si doped $1 \times 10^{19}$ cm$^{-3}$ the required thickness was found to be at least 3μm. The models of Swirhun [97] for minority carrier parameters were used in the simulation.

Fig. 6.3 shows collector currents vs. base-emitter voltage for the above structure ($N_A$(SiGe) = $1 \times 10^{19}$ cm$^{-3}$, $N_A$(Si) = $5 \times 10^{19}$ cm$^{-3}$), as well as bulk Si ($N_A = 1 \times 10^{19}$ cm$^{-3}$, no Si$_{1-x}$Ge$_x$ channel), and bulk Si$_{1-x}$Ge$_x$ (possible in simulation, $N_A = 1 \times 10^{19}$ cm$^{-3}$) devices when no surface recombination is present and $w_B \approx 4L_n$. The collector current in Si$_{0.8}$Ge$_{0.2}$ channel device (realistic structure) is almost identical to the bulk Si$_{0.8}$Ge$_{0.2}$ device. However, the collector current in the all-Si device is much lower ($\sim \exp(-\Delta E_G/k_B T)$). The simulations confirmed the exponential dependence of the collector current on basewidth and that the extracted diffusion lengths were the same in case of bulk Si$_{0.8}$Ge$_{0.2}$ and Si$_{0.8}$Ge$_{0.2}$-channel devices. To further confirm that the lateral electron transport is mainly through the Si$_{0.8}$Ge$_{0.2}$ layer, simulations with different mobilities in Si and Si$_{0.8}$Ge$_{0.2}$ were performed. This is shown in Fig. 6.4. The increase in electron mobility in the Si$_{0.8}$Ge$_{0.2}$ layer increases the collector current, while the change in electron mobility in Si does not affect the current.

After the preliminary structure was designed, surface recombination was introduced in the simulations. Significant surface recombination could cause the measured diffusion length to appear lower than the true one due to a lower effective lifetime. If the effective lifetime were measured independently, one could still extract the correct minority carrier diffusion coefficient in the Si$_{1-x}$Ge$_x$ layer, but not the true lifetime. To first order, if the cap Si layer is thin ($<< L_n$) and the surface recombination veloc-
6. Minority Carrier Properties in Si$_{1-x}$Ge$_x$

Figure 6.3: Simulated collector current density for a Si$_{0.8}$Ge$_{0.2}$ channel device ($w_{\text{SiGe}} = 600\,\text{Å}$, $N_A(\text{SiGe}) = 1 \times 10^{19} \,\text{cm}^{-3}$, $N_A(\text{Si}) = 5 \times 10^{19} \,\text{cm}^{-3}$, $w_{\text{Si, cap}} = 200\,\text{Å}$, $w_{\text{Si, buffer}} = 5\,\mu\text{m}$, $w_B = 15\,\mu\text{m}$), and bulk Si and bulk Si$_{0.8}$Ge$_{0.2}$ devices, ($N_A = 1 \times 10^{19} \,\text{cm}^{-3}$, $w_{\text{vertical}} = 20\,\mu\text{m}$, $w_B = 15\,\mu\text{m}$ in both cases)
Figure 6.4: Simulated collector current density for a Si$_{0.8}$Ge$_{0.2}$ channel device ($w_{Si, cap} = 200\,\text{Å}$, $w_{SiGe} = 600\,\text{Å}$, $w_{Si, buffer} = 5\,\mu\text{m}$) when electron mobilities in Si and Si$_{0.8}$Ge$_{0.2}$ layers are varied.
6. Minority Carrier Properties in Si\(_{1-x}\)Ge\(_x\)

Minority carrier properties in Si\(_{1-x}\)Ge\(_x\) are slow compared to D\(_{n,\text{Si}}/w_{\text{Si,cap}}\) so that the electron quasi Fermi level at the surface is the same as that in the Si\(_{1-x}\)Ge\(_x\), one can write:

\[
\left(\frac{dn}{dt}\right)_{\text{SiGe}} = \frac{n_{\text{SiGe}}}{\tau_{n,\text{eff}}} = \frac{n_{\text{SiGe}}}{\tau_{n,\text{SiGe}}} + \frac{n_{\text{SiGe}}}{w_{\text{SiGe}}} S_{\text{eff}} e^{\frac{-\Delta E_g}{k_B T}}
\]

(6.6)

where \(n_{\text{SiGe}}\) is the electron concentration in Si\(_{1-x}\)Ge\(_x\), \(\tau_{n,\text{eff}}\) is the measured lifetime, \(\tau_{n,\text{SiGe}}\) is the true lifetime in Si\(_{1-x}\)Ge\(_x\), \(S_{\text{eff}}\) is the surface recombination velocity (accounting for any band banding effects at the Si surface) and \(w_{\text{SiGe}}\) is the thickness of the Si\(_{0.8}\)Ge\(_{0.2}\) layer. The effective lifetime can be modeled as:

\[
\tau_{n,\text{eff}} = \left(\frac{1}{\tau_{n,\text{SiGe}}} + \frac{S_{\text{eff}} e^{\frac{-\Delta E_g}{k_B T}}}{w_{\text{SiGe}}}\right)^{-1}
\]

(6.7)

This is illustrated in Fig. 6.5 where the effective lifetime is plotted as a function of the true lifetime for different \(S_{\text{eff}}\). The \(\tau_n\) range in the figure approximately corresponds to the 1 \(\times\) 10\(^{18}\) cm\(^{-3}\) to 5 \(\times\) 10\(^{19}\) cm\(^{-3}\) p-type doping range in Si [97]. For surface recombination to have negligible effects, the following needs to hold:

\[
S_{\text{eff}} e^{\frac{-\Delta E_g}{k_B T}} < \frac{w_{\text{SiGe}}}{\tau_{n,\text{SiGe}}}
\]

(6.8)

Assuming the same minority carrier lifetimes in Si\(_{1-x}\)Ge\(_x\) as in Si (~ 10ns), \(S_{\text{eff}}\) should be below \(~\) 10\(^4\) cm/s. The simulation gives an upper limit to \(S_{\text{eff}}\) of 6000 cm/s. By increasing the thickness of the top Si layer the surface effects are reduced, but thinner top layers are desired for high lateral current ratio (equation 6.5). The thickness for \(S_{\text{eff}} \sim 10^5\) cm/s needs to be above 5000Å.

6.4 Device fabrication

A set of structures was grown to measure minority carrier parameters. A thick (3-5\(\mu\)m) p\(^+\)(1 \(\times\) 10\(^{18}\) cm\(^{-3}\)-5 \(\times\) 10\(^{19}\) cm\(^{-3}\)) Si buffer layer was grown to prevent the diffusion of carriers to p\(^-\) Si substrate in all samples. Si\(_{0.8}\)Ge\(_{0.2}\) layers 600Å thick and 300Å thick were grown with the doping levels varying from 3 \(\times\) 10\(^{17}\) cm\(^{-3}\) to
Figure 6.5: Effective lifetime as a function of true lifetime for various surface recombination velocities
6. Minority Carrier Properties in Si$_{1-x}$Ge$_x$

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<td>180</td>
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Table 6.1: Summary of structural parameters of samples designed for measurements of minority carrier properties

$4 \times 10^{18}$ cm$^{-3}$. Both structures with thick ($\sim 4000$Å) and thin ($\sim 200$Å) p$^+$Si-cap layers were grown ($1.5 \times 10^{19}$ cm$^{-3}$–$2 \times 10^{19}$ cm$^{-3}$). The layer thicknesses and doping levels were measured by SIMS. The actual doping in the Si$_{1-x}$Ge$_x$ layers measured by SIMS was lower (by a factor of 2-3) than expected from B$_2$H$_6$ flows in all samples. The actual Si$_{1-x}$Ge$_x$ layer thicknesses were also lower than predicted from the expected growth rate (by $\sim$1.5). The summary of samples and relevant structure parameters is given in Table 6.1.

To measure the electron diffusion length, we have fabricated devices similar to that of Fig. 6.1 except that the minority carriers were generated by light illumination instead of a forward biased p–n junction. This method was proposed by Misiakos et al. [114]. It is shown in Fig. 6.6.

To minimize the surface recombination, a high quality thermal oxide is desired at Si/SiO$_2$ interface. However, processing of Si/Si$_{1-x}$Ge$_x$ heterojunctions is restricted to temperatures below 800°C. We have used a thin layer ($\sim 50$Å) of thermal oxide
Figure 6.6: Device structure used for diffusion length measurements. The collector contact area was $150 \times 150\mu m^2$, the basewidths ranged from 1$\mu m$ to 30$\mu m$. 
6. Minority Carrier Properties in Si$_{1-x}$Ge$_x$

grown at 700°C (10 min. dry O$_2$ + 40 min wet H$_2$O + 5 min. dry O$_2$ + 10 min N$_2$), as an interface layer, and then deposited 5000Å thick plasma oxide at low temperature (350°C). A surface recombination velocity of below 1000 cm/s is predicted for 2 \times 10^{19} \text{ cm}^{-3} \text{ p-type substrate for a dry O}_2 \text{ oxidation followed by an argon anneal for a high quality Si/SiO}_2 \text{ interface} [115]. Assumimg another factor of 10 higher $S_{\text{eff}}$ due to possible lower quality of our thermal oxides would still give negligible effects.

The oxide was used as an ion implantation mask. Four various implant conditions (both P and As) were used to form the collector. The summary of implant conditions is given in Table 6.2. On some of the samples with thick Si caps, the Si cap layers very partially etched prior to implantation to reduce the Si current path. Device with different implants were processed simultaneously, for comparison. All the implants were annealed at 700°C for 20 minutes.

The entire p-n junction area was covered by the metal contact which laterally extended over the passivating oxide to provide a mask for the uniform light beam, as shown in Fig. 6.6. On one side of the contact the shaded area extended up to a distance $w_B$ (varied 1 - 30\(\mu\)m) while it was much larger on the other sides (150\(\mu\)m). This provides the photocurrent that is a function of basewidth $w_B$ (see the following section).

Ti/Al metalization was used as the collector contact. Devices with 1000Å and 2000Å thick metal were fabricated.

6.5 Diffusion length measurements

Misiakos et al. [116] have derived an analytical expression for lateral photocurrent assuming a thick bulk material. In case of p-Si/p-Si$_{1-x}$Ge$_x$/p-Si structure, the exact expression becomes complicated, but since most of carriers generated are going to be
### Table 6.2: Summary of processing runs and implant conditions

<table>
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</tr>
<tr>
<td>1572-1574, not etched 1569-1571 etched 4000Å</td>
<td>$1 \times 10^{15}$ cm$^{-2}$, 20KeV</td>
<td>900Å</td>
</tr>
<tr>
<td>II</td>
<td>P</td>
<td>3500Å</td>
</tr>
<tr>
<td>1569-1571, etched 1000Å</td>
<td>$1 \times 10^{15}$ cm$^{-2}$, 20KeV + $1 \times 10^{15}$ cm$^{-2}$, 60KeV + $1 \times 10^{15}$ cm$^{-2}$, 100KeV + $1 \times 10^{15}$ cm$^{-2}$, 150KeV</td>
<td>3500Å</td>
</tr>
<tr>
<td>III</td>
<td>P</td>
<td>2500Å</td>
</tr>
<tr>
<td>1569-1571, etched 2000Å</td>
<td>$1 \times 10^{15}$ cm$^{-2}$, 20KeV + $1 \times 10^{15}$ cm$^{-2}$, 60KeV + $1 \times 10^{15}$ cm$^{-2}$, 100KeV</td>
<td>2500Å</td>
</tr>
<tr>
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<td>As</td>
<td>1400Å</td>
</tr>
<tr>
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<td>1400Å</td>
</tr>
</tbody>
</table>

confined to Si$_{1-x}$Ge$_x$ layer, one can approximate photocurrent as:

$$J_{ph} \approx \int_{w_b}^{\infty} q \text{Ge}^{x/L_n} dx = qGL_ne^{-w_b/L_n}$$

(6.9)

where $G$ is the generation rate of carriers per unit area. The exponential dependence on basewidth is the same as in case of a bipolar transistor ($I \propto e^{-w_b/L_n}$), as expected.

A typical measured photogenerated current vs. basewidth is plotted in Fig. 6.7. That the measurement was not affected by the absorption length of the incident light was confirmed by measurements with visible light (microscope lamp on the probe station) and 1.2µm laser. In the case of a visible light source, carriers were mostly generated in Si layers and diffused into the Si$_{1-x}$Ge$_x$ well, while with 1.2µm light source most of the carriers were probably generated within the Si$_{1-x}$Ge$_x$ layer. No
Figure 6.7: Photocurrent vs. basewidth for $N_A = 1.7 \times 10^{18} \text{ cm}^{-3}$ in $\text{Si}_{0.8}\text{Ge}_{0.2}$ layer
difference in the results was observed, within the experimental error. The collector currents were measured at zero bias using HP-4140B pA-meter. The collector currents in devices with thin metal (1000Å) mask did not approach zero at very large basewidths (~10L_n), but rather a constant background current, probably because the thin metal was still transparent for some of the light. This was not the case when the metal thickness was increased to 2000Å. In the case of thin metal devices, the background current was subtracted from the total current to evaluate the diffusion lengths. The same diffusion lengths (within 10%) were found as on the devices with thick metal on the same wafers.

Various implant conditions did not affect the diffusion length results. However, whenever the implant depth reached the Si_{1-x}Ge_x layer, an increased leakage current in base-collector diode characteristics was observed at room temperature (~100nA/1V). This was probably due to implantation damage in Si_{1-x}Ge_x. Enhanced implantation damage in Si_{1-x}Ge_x relative to that in Si for similar implantation conditions has been reported [117]. If the n+ region did not reach the Si_{1-x}Ge_x layer, leakage in p–n junctions was negligible (<1nA/1V). However, if the p–n junction is within the top Si layer and the collecting junction does not reach the Si_{1-x}Ge_x layer, the thin p^+-Si layer between the Si_{1-x}Ge_x channel and the n^+collector presents an additional barrier for electron transport resulting in lower collector current levels. However, if the barrier thickness is small (a few hundred Å) compared to the lateral basewidth (which was always the case in our devices), the collector currents at different basewidths should still scale as exp(-w_B/L_n), so that the same extracted L_n is found. Neither the Si-cap thickness nor the processing variations affected the L_n measurements within the experimental error, so parallel transport in Si cap layer probably did not affect the results.

The room temperature results are summarized in Fig. 6.8. Also shown in the figure are the results for Si reported by Swirhun [97] and Leu and Neugroschel [118].
For heavily doped Si (above $\sim 2 \times 10^{19}$ cm$^{-3}$), the decrease in measured diffusion lengths is attributed to Auger recombination. At lower doping levels, the lifetimes measured in Si from processed samples (reflected in the plotted Si diffusion lengths of Fig. 6.8), were well below the Auger limit, most likely caused by Shockley-Read-Hall (SRH) or trap-assisted Auger processes [97, 118]. Both SRH and trap-assisted Auger recombination are mediated by recombination centers in the bandgap so the measured minority carrier parameters reflect both material and processing quality. Since our samples are all doped well below $1 \times 10^{19}$ cm$^{-3}$ we also expect SRH or trap-assisted Auger processes to dominate. It is clear from Fig. 6.8 that the values obtained for our samples have lower diffusion lengths than similarly doped silicon at room temperature.
We have also performed low temperature measurements. Fig. 6.9 shows the Si$_{0.8}$Ge$_{0.2}$ diffusion length measured at 85K. Also shown for comparison, is the Si data of Swirhun [97] measured at 100K and data of Leu and Neugroschel [118] measured at 77K. There is no sufficient Si data at low temperature published to clearly establish diffusion length vs. doping curve, and the temperature dependence of minority carrier mobility is strongly doping dependent [97], but it is clear from Fig. 6.9 that data points for Si$_{1-x}$Ge$_x$ lie near the published Si data.

We think that the reason for the diffusion lengths compared to Si at room vs. low temperature is not a bulk Si$_{1-x}$Ge$_x$ property, but that the room temperature data is affected by surface recombination due to the limited quality of our passiva-
6. Minority Carrier Properties in Si$_{1-x}$Ge$_x$

If the effective surface recombination velocity is much larger than we expected, the effective lifetime would be much lower resulting in lower measured diffusion lengths. At low temperature however, due to the better confinement of carriers within Si$_{1-x}$Ge$_x$ (exponential factor in equation 6.7), the surface recombination becomes less significant and measured diffusion lengths represent true properties of the material. This was confirmed by temperature dependent PL measurements. It has recently been shown [119] that the photoluminescence (PL) from Si$_{1-x}$Ge$_x$ quantum wells decreases with increasing temperature above 100K due to a low effective lifetime caused by surface recombination at the top Si surface.

To extract minority carrier mobility one still needs to measure the lifetime. If measured at room temperature on the same samples, the true mobility values could be extracted since the same effective lifetime would be measured as that affecting the diffusion length measurements, provided that the surface is passivated in the same manner. One way to measure electron lifetime would be to modulate the light source at a frequency $\omega$, where $\omega \sim 1/\tau$ ($\sim 10$MHz) and use equation 6.4 to calculate lifetimes from DC and AC diffusion lengths [113] or monitor the transient response in the frequency domain [114]. A more straightforward way would be to measure the change in photoconductivity of the sample in time when illuminated with a short light pulse [112]. Finally, all the samples used in this study exhibited strong PL signal at 77K and 10K. By monitoring the PL decay low temperature lifetime could be measured. The lifetime measurement and extraction of a lateral minority carrier diffusion coefficient vs. doping will be subject of future work.

Note that for HBT modeling the vertical (not lateral as given in this chapter) $D_n$ is needed. The strain moves the four conduction band valleys in the growth plane down with respect to the other two in the growth direction. As a result, the electrons traveling in the growth direction will experience the transverse effective mass $m^* = m_t (0.19$ in Si) while those in the growth plane will see $m^*$ given by:
6. Minority Carrier Properties in Si$_{1-x}$Ge$_x$

\[ \frac{1}{m^*} = \frac{1}{m_i} + \frac{1}{m_v}. \]
Assuming that the strain does not affect the band curvatures, one could easily relate vertical and lateral electron mobilities as the ratio of lateral and vertical effective masses.

6.6 Summary

This chapter provides details of Si/Si$_{1-x}$Ge$_x$/Si heterostructure design for the best performance of lateral devices to extract minority carrier parameters in strained Si$_{1-x}$Ge$_x$. The first measurements of the electron diffusion length as a function of p-doping ($2 \times 10^{17}$ cm$^{-3}$ - $4 \times 10^{18}$ cm$^{-3}$) in Si$_{0.8}$Ge$_{0.2}$ are presented. Room temperature results are affected by surface recombination and the diffusion length appears lower than that reported in Si. Effects of the surface recombination are suppressed at low temperature due to better confinement of carriers within the Si$_{1-x}$Ge$_x$ layer. Low temperature diffusion length values (85K) appear similar or slightly higher than reported Si data. This may be due to high quality material (higher lifetimes) or increased minority carrier mobility. Minority carrier lifetime still remains to be measured to extract the electron mobilities.
Chapter 7

Electron Resonant Tunneling in Si/Si$_{1-x}$Ge$_x$

Heterostructures

7.1 Introduction

The main focus of this thesis has been npn Si/Si$_{1-x}$Ge$_x$/Si HBT's, the device in Si/Si$_{1-x}$Ge$_x$ material system which is the most likely to be exploited in industry in the near future. However, opportunities for novel heterojunction device structures in Si-based material system exist beyond HBT's. One interesting vertical-transport devices is a resonant tunneling structure. In chapter 3 we have used p-type resonant tunneling diodes as a tool to characterize Si/Si$_{1-x}$Ge$_x$ interfaces. From the application perspective, resonant tunneling devices are very interesting because of their potential high speed performance [120, 121, 122]. The integration of resonant tunneling diodes into transistor structures opens a field of multifunctional devices which can lead to a reduction in circuit complexity and size. This field has advanced much further in III-V's than in the Si-based material system. Since the first resonant tunneling bipolar transistor operating at room temperature was demonstrated [123], such applications as a multiple state memory [124, 125], a parity generator [126], and a frequency multiplier [127] have been demonstrated in III-V's.
7. Electron Resonant Tunneling in Si/Si$_{1-x}$Ge$_x$ Heterostructures

7.2 Device fabrication

In Si/Si$_{1-x}$Ge$_x$ material system, the resonant tunneling of holes has been extensively studied [72, 73, 74], but the electron resonant tunneling has not received much attention, except for the single report of Ismail et al. [75]. This is mainly due to the energy band configuration, namely the relatively large valence band offset of a strained Si$_{1-x}$Ge$_x$ layer grown on Si substrate, as explained in chapter 2. To achieve the electron resonant tunneling, a certain offset in the conduction band is needed. This can be accomplished by exploiting a strained Si/relaxed Si$_{1-x}$Ge$_x$ heterojunction grown on a relaxed Si$_{1-y}$Ge$_y$ buffer on top of a <100> Si substrate. Such a structure requires a capability of growing high quality, n-type doped, relaxed Si$_{1-x}$Ge$_x$ layers. In these structures, Si layers are subjected to tensile strain. The strain causes splitting of the conduction bands, such that the four valleys in the growth plane move up in energy, while the two valleys in the growth direction move down. The two valleys form the conduction band edge in Si which is actually lower than that of the surrounding SiGe. The conduction band offset is expected to be $\sim 200$meV for Si$_{0.65}$Ge$_{0.35}$/Si heterojunction, while the splitting of conduction bands is predicted to be $\sim 230$meV, calculated according to the model of Van de Walle and Martin [35]. The two-fold degenerate lowest band in the strained Si has a heavy mass in the growth direction ($m_\pi \approx 0.98$). Due to the large conduction band splitting it is expected that only the heavy electrons will be involved in the tunneling process. The schematic conduction band diagram of the structure at zero bias is shown in Fig. 7.1.

The structures were grown by RTCVD on a <100> n-type silicon substrate. A 0.5$\mu$m-thick continuously graded Si$_{1-x}$Ge$_x$ layer was grown at 625°C, up to $x = 0.35$. On top of the graded layer a 1$\mu$m-thick, n-type doped Si$_{0.65}$Ge$_{0.35}$ buffer was grown, doped $\approx 7 \times 10^{18}$cm$^{-3}$ using phosphine as the dopant source. The growth was followed by an in situ anneal at 800°C for an hour, which provided a fully relaxed "substrate"
Figure 7.1: Schematic conduction band diagram at zero bias. Also shown are the different layers: silicon spacers, $w_s = 175\text{Å}$; $\text{Si}_{0.65}\text{Ge}_{0.35}$ barriers, $w_b = 40 - 70\text{Å}$; and Si well, $w_w = 20 - 50\text{Å}$. 
for the double barrier structure. Undoped 175Å wide Si spacers were grown to prevent
dopant diffusion into the barriers and the well. Si$_{0.65}$Ge$_{0.35}$ barriers were grown at 625°C, with the thicknesses nominally varying from 40 to 70Å on different samples. The silicon quantum well was grown at 700°C, and its width varied from 20 to 50Å. On top of the double barrier structure another n-type Si$_{0.65}$Ge$_{0.35}$ ($\approx 0.1\mu$m) layer was grown, with the top 300Å very heavily doped ($\approx 10^{20}\text{cm}^{-3}$) to provide ohmic contacts. The devices were fabricated by a simple mesa process. The metal (Ti/Al) was used as a mesa mask and the contacts were annealed for 20 minutes in forming gas at 350°C. The mesa sidewalls were not passivated. The resulting device structure is shown in Fig. 7.2. The device area varied from $60 \times 60$ to $130 \times 130\mu$m$^2$.

7.3 Results

Symmetric resonant tunneling of electrons for various well and barrier widths was observed for the first time [128]. In earlier work, only a single broad peak for one positive bias was observed [75]. The peak-to-valley ratios of 2 were observed for the sharpest resonance at 4.2K for the devices with the well widths of 25Å and barrier widths of 60Å, as seen from Fig. 7.3. In the I-V curves resonant features start to appear at about 225K (at 240K in dI/dV curves). At 150K (labeled (b) in Fig. 7.3) the two distinct peaks are obvious. When the temperature is further decreased the higher bias peak (labeled HE$_0$) becomes sharper due to the suppression of the background current (thermionic current component and scattering effects), but the lower one (labeled X) becomes weaker, completely disappearing at low temperatures (d). At 4.2K the peak-to-valley ratio is at its largest value for the higher bias resonance. Devices with different well and barrier widths all exhibit similar temperature behaviour, except that the number and strengths of resonances varies. All of the resonances except the lowest are strongest at 4K and decrease with an increase in temperature. The
7. Electron Resonant Tunneling in Si/Si$_{1-x}$Ge$_x$ Heterostructures

Figure 7.2: RTD device structure
Figure 7.3: I-V curves of a device with 25Å well and 60Å barriers (area=70 × 70μm²) at various temperatures: (a) 220K, (b) 150K, (c) 80K, (d) 4.2K.

The lowest energy resonance is not visible below T ≈ 50K, (even in dI/dV), but rapidly increases in strength up to 120-140K, above which it slowly disappears into the increasing background current. The peak current density of the higher bias peak of the device shown in Fig. 7.3 at 80K is 20A/cm², and increases to 800A/cm² as the barrier width is reduced to 40Å (the well width remains constant). The devices with wider wells exhibit more resonant peaks, as expected, due to lower states in the well, but the resonances are weaker compared to the narrower well devices (25Å). Fig. 7.4 shows I-V and dI/dV curves for a device with a 50Å well and 70Å barriers, at 80K. There are four distinct resonances observed in the dI/dV curve. The resonant features are symmetric for positive and negative biases (with respect to the top layer in the structure). In general, the position of resonances for opposite bias polarities
are within 15% for all devices. The symmetric position of the resonances for positive and negative biases implies symmetric spacer thicknesses (within 25Å), which implies negligible phosphorous segregation at the lower n⁺SiGe/Si interface.

We have used a simple first order model to relate resonant features to the calculated states in the quantum well, assuming an electron effective mass of 0.98m₀, no charge buildup in the well, no voltage drop in the emitter and full depletion of the collector spacer. For example, for device with a 50Å well and 70Å barriers, the calculated bias positions corresponding to the ground state, first, second, and third excited state in the well (HE₀ – HE₃) are 42, 165, 369, and 627mV, respectively. The observed bias positions (positive and negative) of the four distinct resonances in the dI/dV curve at 80K were: 112-120, 162-180, 365-400, and 700-900mV. The three higher bias reso-
nances are easily associated with the tunneling to the first three excited levels of the quantum well (HE\textsubscript{1}, HE\textsubscript{2} and HE\textsubscript{3}), but the lowest bias resonance does not fit into the model. Since the ground state energy in the well (HE\textsubscript{0}) is calculated to be only 11meV, tunneling to this state might indeed not be observed, because of too high a Fermi level in the emitter, explaining the absence of the expected 42mV peak, but not the origin of the 112-120mV peak. Similar calculations on the samples with different barrier and well widths gave similar results. A summary of samples is given in Table 7.1. In devices with narrower wells and hence higher HE\textsubscript{0} states, the HE\textsubscript{0} state was observed, but a lower lying anomalous peak was still also seen (as in the devices of figures 7.3 and 7.4). Therefore both, the calculation of resonance positions and the temperature behaviour suggest a different origin of the lowest energy resonance. To our knowledge, this is the first time that such an anomalous temperature dependence of a resonant peak has been reported. A first possible explanation for this behaviour involves the quantization of levels in the accumulation layer expected to form in the emitter (assuming 2-D to 2-D tunneling). At low temperature, only the ground state in the emitter would be occupied, but at high temperatures tunneling could also occur from thermal electrons in the first excited state, yielding a low bias replica from the emitter ground state resonance. However, the shape of I-V curves (figures 7.3 and 7.4) strongly suggests 3-D to 2-D tunneling process (not 2-D to 2-D) [129, 130]. Tunneling through a defect-state, since there is a relatively high concentration of defects present in structures grown on relaxed Si\textsubscript{1-x}Ge\textsubscript{x} buffer layers (∼1 × 10\textsuperscript{7} cm\textsuperscript{-2}), would not explain the temperature behaviour of the anomalous resonance. Finally, we propose a phonon-absorption-assisted resonant tunneling model to explain the temperature behaviour of the lowest-bias resonance [131].
7.4 Phonon-absorption-assisted model

There has been evidence of phonon-emission-assisted tunneling in III-V material system [132]. In this process an electron can tunnel into the well by emitting an LO-phonon near the zone center. Therefore, at higher bias a small replica of the elastic resonance appears in the I-V curve. The voltage difference between the position of the elastic resonance and the phonon-replica is related to the LO-phonon energy.

We propose a model for the low bias feature involving electron tunneling via phonon absorption, as illustrated in Fig. 7.5. An electron of energy \( E \) in the emitter absorbs a phonon to acquire energy \( \hbar \omega_{ph} \) to tunnel into the well state \( (E + \hbar \omega_{ph}) \). As explained earlier, the conduction band in strained silicon is twofold degenerate,
with the heavy electron effective mass along the growth direction (z-axis). The two conduction band minima in silicon lie at $\Delta-$point ($k_z \approx \pm 0.85\pi/a$). This enables phonon-assisted scattering from one valley to another, as illustrated in Fig. 7.6. The transverse momentum is conserved while the absorbed phonon contributes to $k_z$, with the phonon momentum $q$ equal to $2k_z - G \approx 0.3\pi/a$ (where $G$ is the reciprocal lattice vector). Since the optical phonons have relatively high energies ($\approx 62\text{meV}$ at $q = 0$ for Si [86]) we expect acoustic phonons to be involved in this process rather than optical. For a transverse acoustic (TA) phonon in silicon, the energy corresponding to $q = 0.3\pi/a$ is $\approx 13\text{meV}$ [86]. This would give a peak in the I-V curve corresponding
to an energy of 13meV below the true quantum well state. Given the thicknesses of different layers in the structure, the same first order model used earlier to relate energy and voltages for a device with 50Å well and 70Å barriers predicts a shift in bias position of 50mV. For the 50Å well device described earlier, the expected position of the low bias replica of the HE₁ state is then 165 – 50 = 115mV, in surprisingly good agreement with the measured biases of 112-120mV for the anomalous peak. This feature is not observed for higher resonant levels, possibly due to the significant increase in the background current at higher biases.

A careful study of the temperature dependence supports the phonon-absorption hypothesis. The total size of the resonance should be proportional to the number of phonons available (n_{ph}) to be absorbed:

\[ I \propto n_{ph} \propto \frac{1}{e^{\hbar \omega_{ph}/k_b T} - 1} \]  

(7.1)

where \hbar \omega_{ph} is the phonon energy. This qualitatively explains the disappearance of the peak at low temperatures. A quantitative analysis was performed by separating the background current by fitting the I-V data at different temperatures to a third-order piecewise-polynomial curve, excluding the data points at the resonance. The edge bias points of the excluded interval at the resonance were manually selected so that the background current fit exhibited no resonances or features. The actual data and fitted background I-V curves for a 50Å well device at three different temperatures are shown in Fig. 7.7. Fig. 7.8 shows the resulting lowest-bias-resonance strength vs. inverse temperature for different devices. Curves (a) and (b) are data for a device with 25Å well, for positive and negative biases, and curve (c) is data for a 50Å well device. The error in the data points due to the background fitting procedure is expected to be less than 10%. The data points were then fitted to equation 7.1 with the phonon energy and a vertical scaling constant as adjustable parameters, yielding the dashed lines in Fig. 7.8. The resulting phonon energies of 14meV, 16meV and 12meV for
Figure 7.7: I-V curves of the lowest energy resonance for a 50Å well device at three different temperatures
Figure 7.8: Integrated tunneling current for the lowest energy resonance vs. 1000/T for: (a) 25Å well device, positive bias, (b) 25Å well device, negative bias, (c) 50Å well device, positive bias. The dashed lines are fits to phonon population curves (a) \( \hbar \omega = 14\text{meV} \), (b) \( \hbar \omega = 16\text{meV} \), (c) \( \hbar \omega = 12\text{meV} \).
(a),(b) and (c), respectively, are very close to predicted 13meV for the TA-phonon in silicon with $q = 0.3\pi/a$, and strongly support the phonon-absorption-assisted model as the origin of the lowest bias resonance.

Any two-step process, such as phonon absorption and tunneling, requires that the system pass through an intermediate state. In the case of the phonon-absorption-assisted tunneling process the electron may become "hot" by absorbing the phonon (step $a_1$ in Fig. 7.5) prior to tunneling (step $a_2$), so that the intermediate state could be a true existing state in the conduction band of the emitter with a finite lifetime. This is in contrast to tunneling before the phonon absorption (steps $b_1$ and $b_2$ in Fig. 7.5) or to any path for phonon-emission-assisted tunneling where the intermediate state would be only a "virtual" state. Furthermore, after absorbing a phonon ($a_1$), an electron will see a substantially lower tunneling barrier height than following the $b_1 - b_2$ path or any path for phonon emission. Therefore, it is reasonable that transitions through phonon absorption, when allowed by the energy and momentum conservation rules, are more favorable than phonon-emission related transitions. This could explain why no high-energy replicas corresponding to phonon-emission were observed in our samples and why the relative strength of such a resonance is comparable to the true elastic resonance through the level with which it is associated.

A unique feature of the strained Si/Si$_{1-x}$Ge$_x$ system is that low energy (and hence plentiful) acoustic phonons may be involved due to the momentum transfer between the degenerate conduction band minima. In a material system with one band minimum, only high energy zone center optical phonons would be allowed, making such phenomenon much less likely to occur due to a lower number of phonons. That is a possible reason why phonon-absorption-assisted features have not been observed for holes in Si/SiGe or in III-V material systems.
7. Electron Resonant Tunneling in Si/Si$_{1-x}$Ge$_x$ Heterostructures

7.5 Summary

The first symmetric electron resonant tunneling diode, a novel vertical transport device in Si/Si$_{1-x}$Ge$_x$ material system, has been demonstrated. This confirms high quality of RTCVD epitaxial layers and possibly opens a new area of multifunctional devices to be researched. An anomalous temperature dependence of a low bias resonance has been observed. Both the comparison of observed resonances with the calculated states in the well and the temperature behaviour are consistent with a model of phonon-absorption-assisted tunneling.
Table 7.1: Summary of RTD samples

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<th>barrier width (Å)</th>
<th>spacer width (Å)</th>
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<th>observed bias (mV)</th>
<th>temperature dependence</th>
<th>assignment of observed resonance</th>
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<tbody>
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<td>70</td>
<td>175</td>
<td>42 (HE₀) 165 (HE₁) 369 (HE₂) 627 (HE₃)</td>
<td>112-120 162-180 365-400 700-900</td>
<td>anomalous</td>
<td>o.k. HE₁ HE₂ HE₃</td>
</tr>
<tr>
<td></td>
<td>1072 center</td>
<td>40</td>
<td>65</td>
<td>65 (HE₀) 252 (HE₁) 552 (HE₂)</td>
<td>160-170 220-250 600-800</td>
<td>anomalous</td>
<td>o.k. HE₁ HE₂</td>
</tr>
<tr>
<td>1072 edge</td>
<td>15-25</td>
<td>40-60</td>
<td>125-175</td>
<td></td>
<td>180-250 300-450</td>
<td>anomalous</td>
<td>o.k. HE₀</td>
</tr>
<tr>
<td>1149 center</td>
<td>30</td>
<td>50</td>
<td>175</td>
<td>118 (HE₀) 456 (HE₁)</td>
<td>50-55 95-120 426-515</td>
<td>anomalous</td>
<td>o.k. HE₀ HE₁</td>
</tr>
<tr>
<td>1149 edge</td>
<td>10-25</td>
<td>30-50</td>
<td>100-175</td>
<td></td>
<td>150-300 200-500</td>
<td>anomalous</td>
<td>o.k. HE₀</td>
</tr>
</tbody>
</table>
Conclusions and Suggestions for Further Research

8.1 Conclusions

The research leading to this thesis mainly focussed on Si/Si$_{1-x}$Ge$_x$/Si HBT's: issues related to process integration and experimental determination of parameters critical for accurate DC device modeling and design.

The interest in Si/Si$_{1-x}$Ge$_x$/Si HBT's lies in the potential to fabricate high speed devices and circuits, since the HBT structure allows increased base dopings to reduce base sheet resistance and graded germanium profiles to reduce base transit times. Low intrinsic device delay (high $f_T$), low parasitic base resistances, low parasitic capacitances, and optimized load are prerequisites for high speed circuit performance. When integrated into Si technology, processing needs to be adjusted to reduced thermal cycles (to below 800°C) to prevent strain relaxation and minimize dopant diffusion in the base.

All the samples in this work were grown by RTCVD. The quality of epitaxial material and interfaces was studied in a wide pressure range, by means of x-ray reflectivity, photoluminescence and electrical performance of p-type resonant tunneling diodes. An interface roughness of below 5Å was established for high quality epitaxial layers grown at low pressure.

A heavily doped base and a heavily doped emitter in a bipolar transistor lead to
8. Conclusions and Suggestions for Further Research

A $p^+\!-\!n^+$ junction. Tunneling currents in $p^+\!-\!n^+$ base-emitter junction could cause a severe increase in the base current. The doping on the lighter doped side of the junction should not exceed $5 \times 10^{18}$ cm$^{-3}$ in order not to cause significant tunneling. Both tunneling, and boron diffusion can be controlled by carefully designed undoped spacer layers within the Si$_{1-x}$Ge$_x$ base.

From the room temperature collector current measurements, bandgap narrowing in heavily doped Si$_{1-x}$Ge$_x$ layers was extracted in a wide range of p-type dopings and germanium concentrations for the first time. An empirical model for the effective bandgap narrowing relevant for the minority carrier transport in the base was presented. The heavy doping contribution to the effective bandgap narrowing is lower than that in Si, due to the strain-induced splitting of the bands which pushes the Fermi level further into the valence band for a given hole concentration. Furthermore, the design trade-off between the base sheet resistance and gain was clearly presented.

The minority carrier diffusion length was extracted for the first time in p-type Si$_{1-x}$Ge$_x$ as a function of doping from the photocurrent measurements on optimized lateral devices at room temperature and 85K.

Finally, a novel vertical transport device in the Si-based material system, a symmetric electron resonant tunneling diode was demonstrated for the first time. The anomalous temperature behaviour of the lowest bias resonance was explained by phonon-absorption-assisted model.

8.2 Suggestions for future work

This thesis gives the first empirical model of bandgap narrowing (due to Ge and heavy doping) in strained Si$_{1-x}$Ge$_x$ layers obtained from collector current measurements. It would be interesting to observe bandgap narrowing as a function of germanium
concentration and p-type doping in Si$_{1-x}$Ge$_x$ by optical measurements, such as photoluminescence, and compare it to the electrical results. In this way the relationship between the "true" bandgap narrowing and the effective one could be accurately determined and compared to Si.

The minority carrier lifetime in p-Si$_{1-x}$Ge$_x$ still remains to be measured. Combined with the diffusion length measurements presented in this work, this could lead to the first measurement of minority carrier mobility in strained Si$_{1-x}$Ge$_x$, a parameter critical for accurate collector current modeling.

The focus of this work has been p-type material since the base in npn HBT is a heavily p-type doped Si$_{1-x}$Ge$_x$ layer. However, for various device applications, such as pnp HBT for example, n-type material also deserves to be studied.

The integration of HBT's with resonant tunneling structures into multifunctional devices still needs to be demonstrated in Si/Si$_{1-x}$Ge$_x$ material system. This might be easier to accomplish for a pnp HBT where the double barrier for hole transport could be integrated within the vertical structure of the device (in base-emitter space charge region or in the base, for example). Integration of electron resonant tunneling structures requires further improvement in the relaxed buffer layers, in terms of defect densities and high quality material with high minority carrier lifetimes.

Research on other materials, such as silicon-carbide or silicon-germanium-carbon alloys extends the field of heterojunctions on silicon and among other, possible bipolar device applications.

Finally, Si/Si$_{1-x}$Ge$_x$/Si HBT's have been pushing the limits of high speed device performance and integration into silicon bipolar technology. How far this trend will continue still remains to be seen.
Appendix A

Growth and Processing Details

This appendix provides growth details and run-sheets for typical samples of each chapter in this thesis. It also gives processing details for p and n-type resonant tunneling diodes.

A.1 Graded base HBT samples

Samples in this section are related to chapter 2. Graded base HBT test samples (#758 and #759) were grown on n-type (30-60 Ωcm) <100> Si substrates. The standard “clean + buffer” initial sequence was grown prior to base and emitter HBT layers. The 6 min. high temperature buffer layer was not intentionally doped. All layers were grown at 6 torr with constant H₂ flow of 3slpm and DCS flow of 26sccm. The growth sequence for sample #759 is given in Tab. A.1.

AT&T samples (#996–1002, #1011–1018) were grown on patterned wafers without the high temperature buffer layer (only 30 sec clean at 1000°C), and a thin (~180Å) Si layer was grown at 700°C prior to base layer growth. These samples only had 500–700Å (105 sec at 800°C) emitter layer doped ~ 1 x 10¹⁸ cm⁻³ (PH₃ flow of 2.5 sccm).
A. Growth and Processing Details

Table A.1: HBT sample #759, base and emitter growth

<table>
<thead>
<tr>
<th>time (sec)</th>
<th>temperature (°C)</th>
<th>GeH₄ (sccm)</th>
<th>B₂H₆ (sccm)</th>
<th>PH₃ (sccm)</th>
<th>comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>134</td>
<td>625</td>
<td>87</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>134</td>
<td>625</td>
<td>87</td>
<td>335</td>
<td></td>
<td>base layer: 18%, 150Å spacer</td>
</tr>
<tr>
<td>50</td>
<td>625</td>
<td>77</td>
<td>300</td>
<td></td>
<td>5 × 10¹⁹ cm⁻³, 300Å</td>
</tr>
<tr>
<td>57</td>
<td>625</td>
<td>68</td>
<td>265</td>
<td></td>
<td></td>
</tr>
<tr>
<td>64</td>
<td>625</td>
<td>59</td>
<td>232</td>
<td></td>
<td></td>
</tr>
<tr>
<td>75</td>
<td>625</td>
<td>50</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>91</td>
<td>625</td>
<td>41</td>
<td>0</td>
<td></td>
<td>150Å spacer</td>
</tr>
<tr>
<td>115</td>
<td>625</td>
<td>32</td>
<td>0</td>
<td></td>
<td>12%</td>
</tr>
<tr>
<td>10</td>
<td>625</td>
<td>0</td>
<td>0</td>
<td></td>
<td>purge</td>
</tr>
<tr>
<td>60</td>
<td>800</td>
<td>0</td>
<td>0</td>
<td>2.5</td>
<td>emitter layer: 1 × 10¹⁸ cm⁻³, 400Å</td>
</tr>
<tr>
<td>390</td>
<td>800</td>
<td>0</td>
<td>0</td>
<td>25</td>
<td>1 × 10¹⁹ cm⁻³, 2600Å</td>
</tr>
</tbody>
</table>

A.2 Samples for interface roughness study

The growth sequence of sample #1334 is given as an example of a sequence where the Si₁₋ₓGeₓ layer is grown at pressure above 6 torr (Tab. A.2). The Si₁₋ₓGeₓ layer growth followed the standard high-temperature sequence. DCS flow was constant at 26sccm and not interrupted between layers.

The details of the growth of sample #1432 are also given (Tab. A.3). This is the 20-period superlattice sample used for XRD characterization of the low-pressure and
A. Growth and Processing Details

Table A.2: XRR and PL sample #1334, Si$_{1-x}$Ge$_x$ and Si cap layer growth

<table>
<thead>
<tr>
<th>time (sec)</th>
<th>temperature (°C)</th>
<th>pressure (torr)</th>
<th>H$_2$ (slpm)</th>
<th>GeH$_4$ (sccm)</th>
<th>comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>1000</td>
<td>6</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>700</td>
<td>6</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>110</td>
<td>625</td>
<td>6→60</td>
<td>3→4→3</td>
<td></td>
<td>stabilize pressure</td>
</tr>
<tr>
<td>75</td>
<td>625</td>
<td>60</td>
<td>3</td>
<td>100</td>
<td>Si$<em>0.7$Ge$</em>{0.3}$, 250Å</td>
</tr>
<tr>
<td>60</td>
<td>625</td>
<td>60</td>
<td>3</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>300</td>
<td>700</td>
<td>60</td>
<td>3</td>
<td>0</td>
<td>Si cap</td>
</tr>
</tbody>
</table>

low-temperature interfaces.

A.3 P-type resonant tunneling diodes

P-type resonant tunneling structures (#1297, #1336, 6 torr; #1337, 60 torr; and #1374, 220 torr) were grown on p-type (~30Ωcm) <100> Si substrates. The cleaning step consisted of a 2 min. bake at 1000°C and 250 torr. A 5 min. (~1μm thick) buffer layer was doped p-type (B$_2$H$_6$ (10 ppm in H$_2$) flow of 50 sccm). The symmetric, undoped double-barrier structure consisted of a strained Si$_{1-x}$Ge$_x$ well sandwiched between Si barriers and Si$_{1-x}$Ge$_x$ spacer layers which were separating the double-barrier structure from the doped emitter/collector Si regions. All the Si layers were grown at 700°C and Si$_{1-x}$Ge$_x$ layers at 625°C. Si doped layers were doped 2 – 5 × 10$^{19}$ cm$^{-3}$. The top layer was a p$^+$contact Si layer. The growth sequence of sample #1297 is given as an example (Tab. A.4).
Table A.3: Growth details for superlattice sample #1432

<table>
<thead>
<tr>
<th></th>
<th>temperature (°C)</th>
<th>Si carrier flow (sccm)</th>
<th>GeH₄ flow (sccm)</th>
<th>growth rate (Å/min.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si layer</td>
<td>625</td>
<td>silane (0.4% in H₂): 250</td>
<td>-</td>
<td>18.8</td>
</tr>
<tr>
<td>Si₀.₈Ge₀.₂</td>
<td>550</td>
<td>DCS: 26</td>
<td>100</td>
<td>4.6</td>
</tr>
</tbody>
</table>

A.4 Flat-base HBT samples

Flat-base HBT samples with uniform B and Ge concentrations were used in chapter 5 to study the minority and majority carrier properties in strained Si₁₋ₓGeₓ. Chapter 5 provides the list of samples (Tab.5.1). Collectors in these samples were doped via outdiffusion from the n-type doped high-temperature buffer layer. The growth sequence, including the n-buffer, of sample #934 is shown as a typical example (Tab. A.5).

A.5 Lateral SiGe channel devices

The structures designed to study minority carrier parameters in strained Si₁₋ₓGeₓ are discussed in chapter 6, and a list of samples is provided (Tab.6.1). The layers were grown on p-type (8-60Ωcm) <100> Si substrates. The high temperature buffer in these structures was thick (∼3μm), and p⁺ doped (500 sccm B₂H₆ flow). The growth sequence of sample #1570 of the layers following the p⁺ buffer is shown as a typical example (Tab. A.6).
A. Growth and Processing Details

Table A.4: Sample #1297, p-type RTD

<table>
<thead>
<tr>
<th>time (sec)</th>
<th>temperature (°C)</th>
<th>GeH₄ (sccm)</th>
<th>B₂H₆ (sccm)</th>
<th>comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>1000</td>
<td>50</td>
<td></td>
<td>p-Si</td>
</tr>
<tr>
<td>600</td>
<td>700</td>
<td>50</td>
<td></td>
<td>temp. stabilize</td>
</tr>
<tr>
<td>45</td>
<td>625</td>
<td>200</td>
<td></td>
<td>Si₀.₇₅Ge₀.₂₅ spacer, 160Å</td>
</tr>
<tr>
<td>60</td>
<td>625</td>
<td></td>
<td></td>
<td>purge</td>
</tr>
<tr>
<td>100</td>
<td>700</td>
<td></td>
<td></td>
<td>barrier, 50Å</td>
</tr>
<tr>
<td>45</td>
<td>625</td>
<td>200</td>
<td></td>
<td>temp. stabilize</td>
</tr>
<tr>
<td>15</td>
<td>625</td>
<td></td>
<td></td>
<td>Si₀.₇₅Ge₀.₂₅ well, 40Å</td>
</tr>
<tr>
<td>10</td>
<td>625</td>
<td></td>
<td></td>
<td>purge</td>
</tr>
<tr>
<td>100</td>
<td>700</td>
<td></td>
<td></td>
<td>barrier, 50Å</td>
</tr>
<tr>
<td>45</td>
<td>625</td>
<td>200</td>
<td></td>
<td>temp. stabilize</td>
</tr>
<tr>
<td>60</td>
<td>625</td>
<td></td>
<td></td>
<td>Si₀.₇₅Ge₀.₂₅ spacer, 160Å</td>
</tr>
<tr>
<td>10</td>
<td>625</td>
<td>50</td>
<td></td>
<td>p-Si</td>
</tr>
<tr>
<td>600</td>
<td>700</td>
<td>450</td>
<td></td>
<td>p⁺-Si</td>
</tr>
</tbody>
</table>

A.6 N-type resonant tunneling diodes

Double-barrier structures for electron resonant tunneling were grown on relaxed, graded Si₁₋ₓGeₓ buffer layers (see chapter 7), as developed by C.W. Liu. The growth sequence (following the high-temperature buffer) for sample #1072 is given here (Tab. A.7).
A. Growth and Processing Details

Table A.5: Sample #934, flat-base HBT

<table>
<thead>
<tr>
<th>time (sec)</th>
<th>temperature (°C)</th>
<th>GeH₄ (sccm)</th>
<th>B₂H₆ (sccm)</th>
<th>PH₃ (sccm)</th>
<th>comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>1000</td>
<td></td>
<td></td>
<td></td>
<td>clean</td>
</tr>
<tr>
<td>600</td>
<td>1000</td>
<td></td>
<td></td>
<td>2.5</td>
<td>n-buffer</td>
</tr>
<tr>
<td>~ 600</td>
<td>cold</td>
<td></td>
<td></td>
<td></td>
<td>collector</td>
</tr>
<tr>
<td>240</td>
<td>1000</td>
<td></td>
<td></td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>700</td>
<td></td>
<td></td>
<td></td>
<td>temp. stab.</td>
</tr>
<tr>
<td>40</td>
<td>625</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>300</td>
<td>625</td>
<td>50</td>
<td></td>
<td>400</td>
<td>BC Si₀.₈₆Ge₀.₁₄ spacer</td>
</tr>
<tr>
<td>600</td>
<td>625</td>
<td>50</td>
<td></td>
<td></td>
<td>~1 x 10²⁰ cm⁻³ base</td>
</tr>
<tr>
<td>300</td>
<td>625</td>
<td>50</td>
<td></td>
<td></td>
<td>BE Si₀.₈₆Ge₀.₁₄ spacer</td>
</tr>
<tr>
<td>10</td>
<td>625</td>
<td></td>
<td></td>
<td></td>
<td>purge</td>
</tr>
<tr>
<td>450</td>
<td>800</td>
<td></td>
<td></td>
<td>2.5</td>
<td>emitter</td>
</tr>
</tbody>
</table>

A.7 Processing of resonant tunneling diodes

All of the resonant tunneling diodes of chapter 7 (n-type) and most of the RTD devices of chapter 3 (p-type) were processed by a simple mesa process involving only one photolithographic step. P-type devices were also processed by a three-step wet-etch process. There was some differences in the observed I-V curves between the devices from the same wafer processed in different ways (peak-to-valley ratio, peak position), although this might not be process related but due to layer nonuniformity across the wafer. Both of the processes are described. Short anneals (conditions given below) improved peak-to-valley ratios on some devices and moved the peak position towards a slightly lower bias (probably due to lower contact resistance). All the devices with
Table A.6: Sample #1570, lateral transport device

<table>
<thead>
<tr>
<th>time (sec)</th>
<th>temperature (°C)</th>
<th>GeH₄ (sccm)</th>
<th>B₂H₆ (sccm)</th>
<th>comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>420</td>
<td>800</td>
<td></td>
<td>210</td>
<td>~1 x 10¹⁹ cm⁻³ Si</td>
</tr>
<tr>
<td>30</td>
<td>700</td>
<td></td>
<td>35</td>
<td></td>
</tr>
<tr>
<td>180</td>
<td>625</td>
<td>100</td>
<td>→2.5</td>
<td>set flow</td>
</tr>
<tr>
<td>360</td>
<td>625</td>
<td></td>
<td>2.5</td>
<td>p-Si₀.₈ Ge₀.₂ channel</td>
</tr>
<tr>
<td>45</td>
<td>625</td>
<td></td>
<td>→210</td>
<td>set flow</td>
</tr>
<tr>
<td>312</td>
<td>800</td>
<td></td>
<td>210</td>
<td>~1 x 10¹⁹ cm⁻³ Si cap</td>
</tr>
<tr>
<td>7</td>
<td>800</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

only Al metalization (no Ti) did not survive the 10min anneal at 400°C (probably due to Al spiking).

Singe-step process

- initial RCA clean
- metal evaporation (e-beam evaporator: 500Å Ti + 2000Å Al or just 2500Å Al in some cases)
- photolitography (define mesas)
- metal etch (Al etch + HF : H₂O(1 : 100) for Ti)
- plasma etch using metal mask (SF₆ only 15sccm, 150mtorr, 100W, 0.4min ~ 5000-6000Å)
- photoresist strip
- clean HF : H₂O(1 : 50), 30 sec
- Al evaporation on the back or in the corner for the bottom electrode
A. Growth and Processing Details

- anneal (on some samples, $400^\circ\mathrm{C}$, 10-15 min, $\mathrm{N}_2$)

\textit{Wet-etch process}

- initial clean
- photolithography (define mesas)
- wet mesa etch (5000-6000Å)
- photoresist strip
- photolithography (for bottom contact lift-off)
- clean HF : $\mathrm{H}_2\mathrm{O}(1 : 10)$, 30 sec
- metal evaporation (e-beam evaporator: 3000Å Al)
- lift-off
- RTA ($450^\circ\mathrm{C}$, 5 min, $\mathrm{N}_2$
- photolithography (for top contact lift-off)
- clean HF : $\mathrm{H}_2\mathrm{O}(1 : 10)$, 30 sec
- metal evaporation (e-beam evaporator: 3000Å Al)
- lift-off
- RTA ($380^\circ\mathrm{C}$, 3 min, $\mathrm{N}_2$)
### A. Growth and Processing Details

Table A.7: Sample #1072, n-type RTD

<table>
<thead>
<tr>
<th>time (sec)</th>
<th>temperature (°C)</th>
<th>GeH₄ (sccm)</th>
<th>PH₃ (sccm)</th>
<th>comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>1000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>700</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>625</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3000</td>
<td>625</td>
<td>0–35</td>
<td>14</td>
<td>1-10%, ~1000Å</td>
</tr>
<tr>
<td>2400</td>
<td>625</td>
<td>35–100</td>
<td>14</td>
<td>10-20%, ~2500Å</td>
</tr>
<tr>
<td>780</td>
<td>625</td>
<td>100–450</td>
<td>14</td>
<td>20-35%, ~2600Å</td>
</tr>
<tr>
<td>1500</td>
<td>625</td>
<td>450</td>
<td>14</td>
<td>Si₀.₆₅ Ge₀.₃₅, 7500Å anneal</td>
</tr>
<tr>
<td>3600</td>
<td>800</td>
<td></td>
<td></td>
<td>set temp.</td>
</tr>
<tr>
<td>45</td>
<td>625</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>625</td>
<td>450</td>
<td></td>
<td>Si spacer, 175Å set temp.</td>
</tr>
<tr>
<td>350</td>
<td>700</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>45</td>
<td>625</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>625</td>
<td>450</td>
<td></td>
<td>Si₀.₆₅ Ge₀.₃₅ barrier, 70Å purge</td>
</tr>
<tr>
<td>100</td>
<td>700</td>
<td></td>
<td></td>
<td>Si well, 50Å set temp.</td>
</tr>
<tr>
<td>45</td>
<td>625</td>
<td></td>
<td></td>
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<tr>
<td>14</td>
<td>625</td>
<td>450</td>
<td></td>
<td>Si₀.₆₅ Ge₀.₃₅ barrier, 70Å purge</td>
</tr>
<tr>
<td>10</td>
<td>625</td>
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<tr>
<td>350</td>
<td>700</td>
<td></td>
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<td>Si spacer, 175Å set temp.</td>
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<td>625</td>
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<tr>
<td>120</td>
<td>625</td>
<td>450</td>
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<td>n–Si₀.₆₅ Ge₀.₃₅, 600Å</td>
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<td>450</td>
<td>150</td>
<td>n⁺–Si₀.₆₅ Ge₀.₃₅ contact layer</td>
</tr>
</tbody>
</table>
Appendix B

Publications and Presentations Resulting from this Thesis

1. Ž. Matutinović Krstelj, E. Chason, and J. C. Sturm, “Growth pressure effects on Si$_{1-x}$Ge$_x$ CVD”, submitted for publication to J. of Electronic Materials.


References


