Alloy scattering limited transport of two-dimensional carriers in strained $Si_{1-x}Ge_x$ quantum wells

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The mobility of two-dimensional electron systems in strained $Si_{1-x}Ge_x$ quantum wells was studied at low temperatures as a function of the germanium content in the well. While mobilities exceeding 30 000 cm^2/V s have been achieved for pure Si layers, they dropped to less than 3000 cm^2/V s for $Si_{0.88}Ge_{0.12}$ wells, demonstrating the effect of strong alloy disorder scattering. This was confirmed by the relatively weaker dependence of mobility on carrier concentration in gating experiments. By accounting for valley degeneracy effects in the standard two-dimensional alloy scattering model, an effective scattering potential $V_{alloy}=0.8\pm0.1$ eV has been derived for electrons. Using a weaker potential, it is shown that the maximum low temperature mobilities for holes reported in literature are also consistent with the alloy scattering model.

Two-dimensional (2D) electron and hole gases in Si/$Si_{1-x}Ge_x$ modulation-doped heterostructures on ⟨100⟩ Si substrates have been investigated by a number of groups in the past few years.[1–4] Typically holes have been studied in compressively strained $Si_{1-x}Ge_x$ layers grown pseudomorphically on Si ⟨100⟩ substrates, and electrons have been studied in tensilely strained pure Si grown pseudomorphically on relaxed $Si_{1-x}Ge_x$ buffer layers, in turn grown on Si ⟨100⟩ substrates. Although low temperature electron mobilities have recently surpassed 170 000 cm^2/V s,[2] the maximum low temperature hole mobility has remained below 7000 cm^2/V s.[3] It has been speculated that scattering due to the random disorder potential in the $Si_{1-x}Ge_x$ alloy degrades hole transport while not affecting electron transport, since the latter occurs in pure Si layers.[1] Although alloy scattering was studied many years ago in bulk $Si_{1-x}Ge_x$ alloys,[5] it has been ignored in SiGe 2D structures to date. In this work, low temperature transport of two-dimensional electron gases in $Si_{1-x}Ge_x$ alloys is studied for the first time, thus making possible a direct comparison of electrons and holes and resulting in a quantitative measure of the alloy scattering potential.

The modulation-doped structures used in this work were grown by rapid thermal chemical vapor deposition (RTCVD) on ⟨100⟩ Si substrates. A graded, relaxed $Si_{1-x}Ge_x$ layer followed by a relaxed $Si_{0.62}Ge_{0.38}$ buffer were first grown, followed by the undoped strained $Si_{1-x}Ge_x$ transport layer, an undoped 100 Å spacer, and finally an *n*-type-doped $Si_{0.62}Ge_{0.38}$ layer for the modulation doping. Further details of growth conditions and sample structure can be found in Ref. 6. Typical threading dislocation densities in the active layers are 10^7 cm^{-2}. The Hall mobility and carrier concentration for three samples with 0%, 12%, and 20% germanium in the well are displayed in Fig. 1 as a function of temperature. For each sample, the mobility increases as sample temperature decreases. At the same time, carrier concentration decreases and saturates at low temperatures with no sign of freeze out, indicating the presence of a two-dimensional electron gas (2DEG) in all the samples. A 2DEG and no parallel conduction has been confirmed in similar samples by high field magnetotransport experiments previously.[6] The maximum low temperature (10 K) mobility is strongly degraded with increasing germanium content in the well, indicating transport dominated by alloy scattering. A small part of the degradation is due to loss of screening of impurities since, for larger x, the smaller conduction-band offset between the $Si_{0.62}Ge_{0.38}$ barrier and the $Si_{1-x}Ge_x$ well results in smaller carrier transfer. The experimental data for four different samples are summarized in Table I.

To estimate the strength of the alloy scattering potential, it is necessary to extract the mobility limited by alloy scattering from the measured mobilities. We assume that $\mu_{meas}^{-1}=\mu_{imp}^{-1}+\mu_{alloy}^{-1}$, where μ_{meas} is the measured mobility, μ_{alloy} is the mobility limited by alloy scattering, and μ_{imp} is the mobility limited by impurity and all other scattering mechanisms. The use of Matthiessen's rule to calculate the total mobility is valid in degenerate systems at low temperatures. From a previous study,[6] we determined that for large spacer widths (> 80 Å), electron mobilities in pure Si channels grown in our system were limited by a background impurity concentration of $\sim 10^{16}$ cm^{-3}. Assuming the same background impurity concentration as the $x=0$ sample and scaling $\mu_{imp}\sim\sqrt{n}$, where n is the two-dimensional carrier concentration[7] for other samples, we can calculate μ_{imp} and hence extract μ_{alloy}. The extracted mobilities are also displayed in Table I. The errors given on μ_{alloy} represent a possible factor of 2 variation in background impurity concentration from the control ($x=0$) sample.

The alloy scattering limited mobility of a two-dimensional electron gas at low temperatures is given by[7]

$$\mu_{alloy}=\frac{e\hbar^3}{m_{xy}^2\Omega_0 V_{alloy}^2 x(1-x)}\left(\frac{16}{3b}\right), \tag{1}$$

where m_{xy} is the transverse effective mass (in the plane of the 2D gas), Ω_0 is the atomic volume, V_{alloy} is the alloy disorder potential, and x is the concentration of the binary alloy. b is a variational parameter given by

$$b=\left(\frac{33m_z e^2 n}{8\epsilon\hbar^2}\right)^{1/3}, \tag{2}$$

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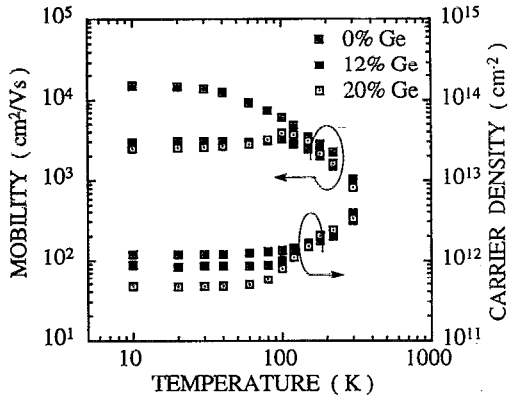

FIG. 1. Temperature-dependent Hall measurements for three samples with 0%, 12%, and 20% germanium in the 75 Å quantum well. All samples had a nominal 100 Å spacer and a 10^{19} cm^{-3} n^+ cap layer.

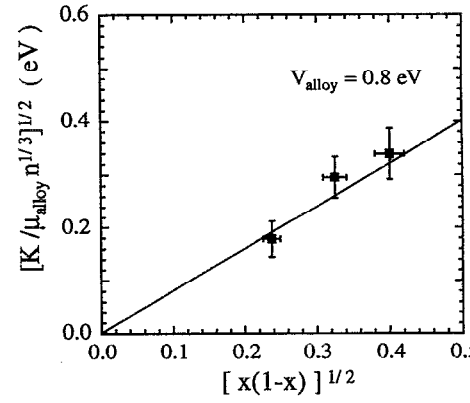

FIG. 2. Alloy scattering model calculations displayed with V_{alloy} as an independent parameter. K is a material dependent parameter defined in the text, while μ_{alloy}, n, and x are experimental values from Table I. The data are best fit by $V_{alloy}=0.8\pm0.1$ eV given by the slope of the solid line.

where m_z is the longitudinal effective mass. Thus, the alloy mobility theoretically has a weak dependence on the carrier concentration ($\mu_{alloy}\sim n^{-1/3}$). It should be noted that the classical formula for alloy mobilities in three-dimensional systems diverges at low temperatures and cannot be used for 2D systems.

The above formula assumes intravalley scattering only in a single valley system. In our samples, the sixfold degenerate Si-like conduction-band valleys are strain split into two lower valleys (with heavy mass along the growth direction) and four upper valleys which has been observed in magnetotransport experiments.[1,2,6] The short range nature of alloy scattering should effectively couple states with large differences in the crystal momentum. It is therefore expected that intervalley scattering and intravalley scattering due to alloy effects are comparable in magnitude, which will lower the alloy mobility by a factor equal to the degeneracy of the band minimum g_v. We finally obtain

$$\mu_{alloy}=\frac{e\hbar^3}{g_v m_{xy}^2\Omega_0 V_{alloy}^2 x(1-x)}\left(\frac{16}{3b}\right)\equiv\frac{K}{V_{alloy}^2 x(1-x)n^{1/3}}. \tag{3}$$

This expression depends strongly on m_{xy} but only weakly on other material parameters like ϵ and m_z. We use $m_{xy}=(0.19+0.10x)m_0$ as an interpolation between bulk Si and Ge transverse masses at the Δ point.[8] The calculations are displayed in Fig. 2 along with experimental data from Table I. The error bars reflect maximum uncertainties in m_{xy} and μ_{alloy}. The data can be best fitted by $V_{alloy}=0.8\pm0.1$ eV. Previously V_{alloy} for electrons was estimated as the conduction-band offset between the constituent elements of the alloy.[7] Although in our case V_{alloy} is close to the difference in Si-like conduction-band edges between strained Si and Ge on the relaxed substrate, it has to be treated as an empirical parameter at this point due to the complicated nature of the strained indirect bands.

TABLE I. Summary of experimental data from Hall measurements at 10 K for four different samples. The last column is the extracted alloy-scattering-limited mobility as explained in the text. The errors specified in μ_{alloy} represent possible factor of 2 variations in the background impurity concentration.

x	n (10^{11} cm^{-2})	μ_{meas} (cm^2/V s)	μ_{imp} (cm^2/V s)	μ_{alloy} (cm^2/V s)
0.00	12.0	20000	20000	...
0.06	14.0	6420	21600	9130±30%
0.12	8.8	3000	17130	3640±16%
0.20	4.7	2500	12520	3120±18%

To confirm that alloy scattering and not impurity scattering is responsible for the low mobility in the $x>0$ structures, mobility as a function of carrier concentration was studied in gated Hall bars (front Al gate self-aligned to the mesa). The samples had a structure similar to those above except that the doping was reduced to a thin 3×10^{18} cm^{-3} layer followed by an undoped 400 Å cap. This ensured complete depletion of the doped layer and low gate leakage currents. The spacer was also reduced to 40 Å to ensure adequate carrier transfer for the smallest band offset, with the result that the mobility for the pure Si (0% Ge) well was dominated by remote ionized impurity scattering. Figure 3 shows the mobility as a function of carrier concentration ($\mu\sim n^\gamma$) for two samples with 0% and 12% ger-

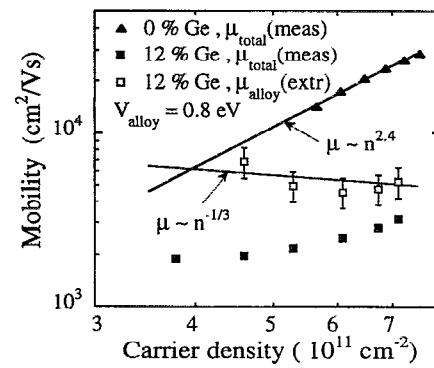

FIG. 3. Mobility as a function of carrier concentration for two similar structures with 0% and 12% Ge quantum wells. Solid triangles and squares are measured data while open squares are extracted alloy mobilities after subtracting impurity scattering. Lines represent best fits to the data given by $\mu\sim n^{2.4}$ for impurity scattering and $\mu\sim n^{-1/3}$ for alloy scattering.

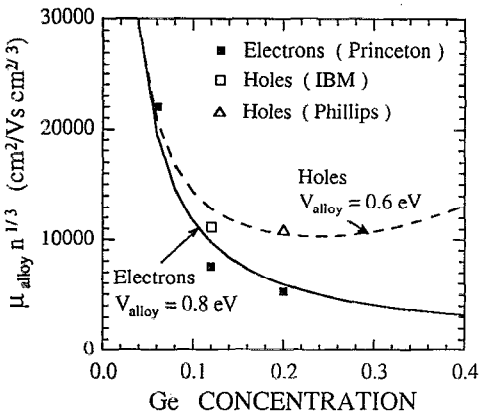

FIG. 4. Calculated alloy scattering limited mobility (in cm^2/V s) of electrons (V_{alloy}=0.8 eV) and holes (V_{alloy}=0.6 eV), normalized by the carrier concentration (in 10^{11} cm^{-2}) as a function of germanium content. The solid squares are experimental data from Table I while the open symbols represent maximum low temperature hole mobilities reported in Refs. 3 and 4.

manium in the quantum well. To the best of our knowledge, these are the first gated mobility results reported for two dimensional gases in Si/$Si_{1-x}Ge_x$ heterostructures. The mobility shows a strong dependence on carrier concentration for the pure Si well, characteristic of remote impurity scattering. The value of the exponent, γ=2.4 is close to that normally observed in AlGaAs/GaAs modulation-doped structures (γ=1.5–2.0).[9] After subtracting this impurity scattering component for the 12% Ge sample, the extracted alloy mobilities (Fig. 3) show the correct carrier concentration dependence ($\mu \sim n^{-1/3}$) as predicted by the model. This confirms alloy scattering dominated transport.

Figure 4 shows μ_{alloy} normalized by $n^{-1/3}$ as a function of germanium content. Using the model, a good fit is obtained for V_{alloy}=0.8 eV as determined above. Also plotted are maximum low temperature hole mobilities reported in literature for strained $Si_{1-x}Ge_x$ layers on Si substrates.[3,4] Previous workers have attributed the low mobility of holes to either remote impurity scattering[3,4] or poor sample quality. As can be seen, however, their results fit well to the alloy scattering model using V_{alloy}=0.6 eV. Note that no intervalley scattering was included for holes since the normally degenerate valence band is split by strain. For the hole effective mass, a linear interpolation, $m_{xy}=(0.44-0.42x)m_0$ was found to fit experimentally determined values.[10] From the good fit to data, one concludes that the limit is indeed alloy scattering and not other sample dependent effects. That V_{alloy} for holes is less than that for electrons is not totally unexpected. A similar trend has been observed in III-V alloys.[11]

In conclusion, two-dimensional electron gases have been fabricated in strained $Si_{1-x}Ge_x$ quantum wells to probe the strength of alloy scattering in 2D SiGe systems for the first time. From low temperature mobilities, an effective electron alloy scattering potential of V_{alloy}=0.8 ±0.1 eV has been derived which reflects both intravalley and intervalley scattering. This alloy scattering model is also consistent with experimental data for two-dimensional hole gases in similar structures using V_{alloy}=0.6 eV.

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