lower temperature of 660 °C, there was growth on areas not covered by SiO_2 similar to that at 680 °C. In addition, there were a few speckles of deposit on SiO_2. Scanning electron microprobe examination of the deposit showed its composition to be GaAs. At a still lower temperature of 640 °C, there was growth on open areas as usual, but the density of the GaAs speckles on SiO_2 had increased to more than tenfold compared to that at 660 °C. However, with subsequent removal of SiO_2 by HF treatment, these deposits were easily removed. At a still lower temperature of 620 °C, continuous polycrystalline deposits were formed on SiO_2 while single crystal growth was still maintained on open areas. Figure 3 shows the growth at different temperatures.

In conclusion, selective growth on open areas of (100) gallium arsenide surface has been shown to be possible without any deposit in areas covered with SiO_2. This is quite significant because it would make the growth of material for a particular type of device at selected areas of the wafer possible. That way, a number of devices of different types can be fabricated on a single wafer and different types of integrated circuit structures would be possible. To our knowledge, such selective growth by MOVPE is being reported for the first time.

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Modulation doping in Ge_xSi_{1-x}/Si strained layer heterostructures

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We report the first observation of the modulation doping effect in Si/$Ge_{0.2}Si_{0.8}$ heterojunctions grown by molecular beam epitaxy. Peak hole mobilities of $\sim 3300\ \mathrm{cm^2\,V^{-1}\,s^{-1}}$ have been observed at 4.2 K. These values, although nonoptimum, are comparable to the best reported values for holes in Si/SiO_2 inversion layers. Low temperature, angular dependent, Shubnikov–de Haas measurements have demonstrated the two-dimensional nature of the hole gas and yield a surface carrier density of $3.5 \times 10^{11}\ \mathrm{cm^{-2}}$. From the temperature dependence of the Shubnikov–de Haas amplitudes a hole effective mass of $0.30 \pm 0.02 m_o$ has been derived. Identical measurements on n-type heterojunctions having the same Ge content ($x = 0.2$) have failed to show a sustained enhancement of mobility at low temperatures, indicating that $\Delta E_v \gg \Delta E_c$.

Heteroepitaxy of Si/Ge_xSi_{1-x} offers exciting possibilities for intergrated optoelectronics and novel field-effect transistor (FET) structures. In addition to such potential applications this system also offers a unique opportunity for investigation of the effects of misfit strain on the transport properties of indirect gap semiconductor heterointerfaces and strained layer superlattices[1] since the lattice mismatch between Si and Ge is $\sim 4\%$.

Recent progress in silicon molecular beam epitaxy (Si MBE)[2] coupled with a quantitative determination of growth parameters pertinent to the pseudomorphic growth of Ge_xSi_{1-x}/Si strained layers[3] has made it possible for us to achieve the first two-dimensional hole gas at a Si/$Ge_{0.2}Si_{0.8}$ heterointerface. In this letter we explore the enhanced transport properties made possible due to modulation doping of the Si/Ge_xSi_{1-x} interface. Such investigations are of obvious importance for the implementation of FET devices and moreover shed light on the relative band alignment between Si and Ge_xSi_{1-x}, since the occurrence of modulation doping requires a sufficiently large discontinuity in the band edge.

Data on the indirect gap of bulk Ge_xSi_{1-x} alloys can be found in the work of Braunstein *et al.*[4]; however, measurements of the band discontinuities for Si/Ge_xSi_{1-x} heterojunctions tend to vary over a large margin.[5,6] At $x = 0.2$ the band-gap difference ΔE_g is estimated to be 0.10 eV.[4] It should be noted that this value of ΔE_g is comparable to the valence-band step ΔE_v for $Al_{0.5}Ga_{0.5}As$/GaAs for which the modulation doping effect for holes has been observed[7]; therefore, if in the present system $\Delta E_v \gg \Delta E_c$ then one would expect to observe modulation doping due to the similarity of the valence-band structure of GaAs and Si. (This similarity is due primarily to the absence of inversion symmetry produced by the presence of a heterointerface.)

Figure 1 shows a schematic of the band diagram for a modulation doped P^+-Si/i-$Ge_{0.2}Si_{0.8}$ heterojunction in which it has been assumed that $\Delta E_v \gg \Delta E_c$. In order to maintain a constant Fermi level throughout the sample, ionized

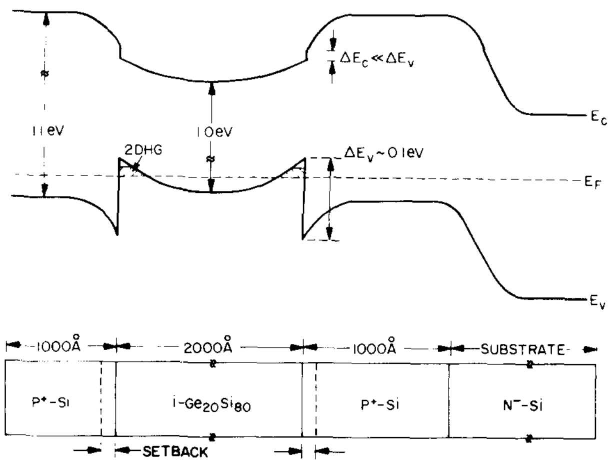

FIG. 1. Band bending diagram for P^+-Si/i-$Ge_{0.2}Si_{0.8}$/P^+-Si strained layer double heterostructure on N^--Si substrate. Typical doping setback value is 100 Å and values for the indirect band gap of $Ge_{0.2}Si_{0.8}$ are from Ref. 4.

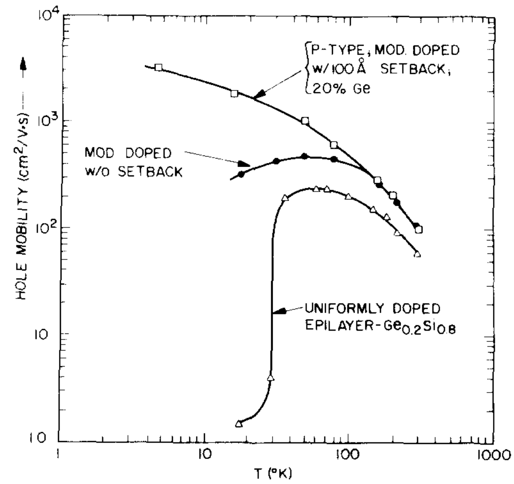

FIG. 2. Hall mobility vs temperature: (a) lower curve corresponds to a uniformly doped $Ge_{0.2}Si_{0.8}$ epilayer of 2000-Å thickness having $N_A - N_D \approx 10^{18}$ cm^{-3}, (b) center curve corresponds to a modulation-doped double heterostructure identical to Fig. 1 except without doping setback, (c) upper curve corresponds to same structure as center curve, except for 100 Å doping setback.

boron acceptors in the Si transfer their holes to the $Ge_{0.2}Si_{0.8}$ valence-band channel which is $\Delta E_v \approx 100$ meV lower in energy. This is the essence of the modulation doping effect[8] wherein ionized acceptors are spatially separated from the conducting medium resulting in a significant reduction in ionized impurity scattering and thus improving the mobility at low temperatures.

Si/Ge_xSi_{1-x} double heterostructures were grown in a P^+-Si/i-Ge_xSi_{1-x}/P^+-Si configuration on lightly doped n-type (v) — ⟨100⟩ Si substrates, as shown in Fig. 1, using the Si MBE system described elsewhere.[9] The wide gap Si layers were deliberately doped with boron to a level $N_A \approx 10^{18}$ cm^{-3}, while the narrow gap Ge_xSi_{1-x} layer was not intentionally doped. We shall mainly concern ourselves with data obtained from samples with $x = 0.2$ and in which both Si layers were 0.1 μm thick. Samples were contacted by evaporating Al and sintering at ~550 °C.

In Fig. 2 we show the resuts of Hall mobility measurements for three samples using the standard van der Pauw technique. The lower curve corresponds to a uniformly doped epilayer of $Ge_{0.2}Si_{0.8}$ ($N_A \simeq 10^{18}$ cm^{-3}) on a v — ⟨100⟩ Si substrate. The freeze-out behavior for $T \lesssim 50$ K is typical of 10^{18} cm^{-3} p-type bulk silicon.[10] The two upper curves are for modulation-doped heterostructures differing only in that the lower of these two curves was grown without a doping setback.[11] The upper curves exhibit three major features at low temperatures which are characteristic of modulation doping[8]: (1) peak hall mobilities are unusually high for bulk Si with an acceptor concentration of 10^{18} cm^{-3},[10] (2) no strong fall-off in mobility due to ionized impurity scattering is observed in going to very low temperatures (the slight reduction observed in the sample having no doping setback is to be expected), (3) the carrier density does not show freeze-out saturating at a level of $\lesssim 10^{12}$ cm^{-2} at 4.2 K. These observations are consistent with the existence of an enhanced mobility two-dimensional hole gas (2DHG) at the Si/$Ge_{0.2}Si_{0.8}$ interface. From the 4.2 K value of the Hall coefficient we derive a carrier surface density of $n_H \simeq 6.7 \times 10^{11}$ cm^{-2} and a Hall mobility of 3300 cm^2 V^{-1} s^{-1}, for the upper curve in Fig. 2. The maximum observed mobility is most likely not a limiting value since we have detected a non-negligible residual doping ($\gtrsim 10^{15}$ cm^{-3}) in the channel region. This mobility value exceeds the highest reported mobility values for p-type Si inversion layers in metal-oxide-semiconductor structures,[12] but remains roughly an order of magnitude below the best values known for a 2DHG in GaAs/$Al_xGa_{1-x}As$.

Further confirmation of the existence of a 2DHG was obtained via oscillatory-magnetoresistance [Shubnikov–de Haas (SdH)] measurements.[8,13] Figure 3 shows the strong dependence of the SdH peak positions on the angle between the magnetic field **H** and the normal to the epilayers. Experimental results show the typical cos θ dependence expected for a two-dimensional system. The oscillation period in reciprocal field $\Delta(1/H) = 1.38 \times 10^{-2}$ kG^{-1} for $H_o \lesssim 50$ kG. A surface charge density $n_s = 3.5 \times 10^{11}$ cm^{-2} was derived from the **H**⊥ layers data, using the expression $n_s = (g_s g_v e/hc)[\Delta(1/H)]^{-1}$ and assuming a valley degeneracy $g_v = 1$ and

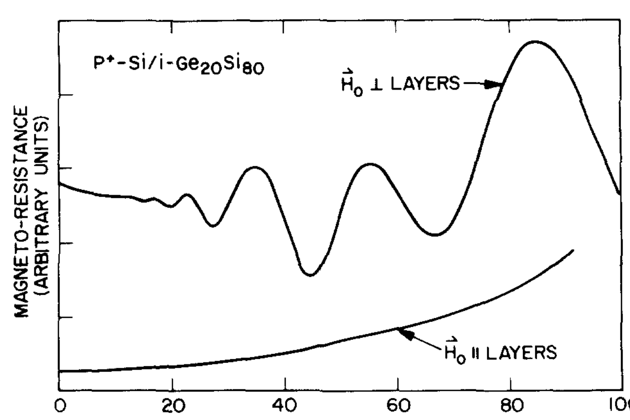

FIG. 3. Shubnikov–de Haas (SdH) data at 1.8 K for upper curve in Fig. 2. The strong angular dependence of the SdH peak positions confirms the two-dimensional nature of the hole gas at the Si/$Ge_{0.2}Si_{0.8}$ interface. From the period in $\Delta(1/H)$ a surface density $n_s = 3.5 \times 10^{11}$ cm^{-2} is determined (for $H_o \lesssim 50$ kG). For $H_o \gtrsim 50$ kG a second period occurs for which $\Delta(1/H)$ decreases by $\approx$ factor of 2; the origin of this feature remains unidentified at present.

spin degeneracy $g_s = 2$. This SdH surface charge density differs by roughly a factor of 2 from the Hall value of 6.7×10^{11} cm^{-2}. This is to be expected if both heterointerfaces in Fig. 1 have a 2DHG associated with them. For $H_o \gtrsim 50$ kG the period of the oscillation changes to $\Delta(1/H) = 7\times10^{-3}$ kG^{-1}, which corresponds to value of n_s closer to the Hall value (if we maintain a spin degeneracy $g_s = 2$). If, however, we assume $g_s = 1$ in the high field regime, then the SdH value of n_s is unchanged and the low field data could be explained in terms of an unresolved spin splitting. At present these results are not clearly understood (since the onset of spin splitting typically shows a characteristic behavior which differs from that we have observed); further work on this issue is in progress.

In order to determine the carrier effective mass, we measure the temperature dependence of the SdH amplitudes between 1.8 and 4.2 K. We used[14]

$$A_{sdH} \sim T\,[\sinh(2\pi^2 k_B T m^*_{hh} c/e\hbar H_o)]^{-1}.$$

Data reduction via this expression gives a carrier mass $m^* \simeq 0.30 \pm 0.02 m_o$ at $H_o = 35$ kG. This value deviates from the linear interpolation value of $m^*_{hh}(x = 0.2) \simeq 0.45 m_o$; the observation of a slightly smaller carrier mass may be due to coherent stain. Using the SdH carrier mass $m^* = 0.30 m_o$ we derive a Fermi energy $E_F \simeq 3$ meV and a scattering time $\tau \sim 6\times10^{-13}$ s for the 2DHG.

Results of identical measurements on n-type samples having the same Ge content ($x = 0.2$) have failed to show a sustained enhancement of carrier mobility at low temperatures. The transferred surface charge density for electrons (n_s) is roughly an order of magnitude smaller than for holes and shows freeze-out behavior for $T \lesssim 30$ K. This observation gives an indication that $\Delta E_v \gg \Delta E_c$, since n_s is proportional to the majority-carrier band discontinuity. These results are in agreement with the earlier work of Kuech *et al.*[6]

In conclusion, we report the first observation of a two-dimensional hole gas at the interface of a $Si/Ge_{0.2}Si_{0.8}$ strained layer heterojunction. Peak holes mobilities ~ 3300 cm^2 V^{-1} s^{-1} have been observed at 4.2 K. Low-temperature oscillatory magnetoresistance (SdH) measurements prove the existence of a 2DHG and yield a carrier surface density of 3.5×10^{11} cm^{-2}. Assuming a carrier mass $m^* = 0.30 m_o$, as determined from the temperature dependence of the SdH amplitudes, we derive a scattering time $\tau \sim 6\times10^{-13}$ s and a Fermi energy of 3 meV.

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