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# Twodimensional electron gas at a molecular beam epitaxialgrown, selectively doped, In0.53Ga0.47AsIn0.48Al0.52As interface

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TABLE II. Reversible photoelectronic effects in lightly phosphorous-doped amorphous silicon in both device and Gap-cell configurations.

| State | Sample Configuration | $I_0$ (A) | $n$ | $\sigma_{DARK}$ $(\Omega\ cm)^{-1}$ | $\Delta E$ (eV) |
|---|---|---|---|---|---|
| PM | SB device | $1\times10^{-11}$ | 1.22 | $1\times10^{-7}$ | |
| | Gap-cell | ... | ... | $3\times10^{-5}$ | 0.35 |
| B | SB device | $1\times10^{-11}$ | 1.25 | $3\times10^{-8}$ | |
| | Gap-cell | ... | ... | $5\times10^{-8}$ | 0.65 |
| A | SB device | $4\times10^{-10}$ | 1.17 | $2\times10^{-7}$ | |
| | Gap-cell | ... | ... | $3\times10^{-4}$ | 0.27 |

con films and concluded that this was caused by band bending at the surface of these films. The variation in magnitude of the surface effect with Fermi level position may be caused by dopants which could alter the surface state density. Heavy doping would increase the bulk density of states and hence reduce band bending.

The above results lead us to conclude that upon illumination and subsequent annealing photoelectronic changes occur both in the bulk of amorphous silicon and at the surface, but that these two effects are caused by entirely different processes. The bulk effect represents a reversible conductivity change and most likely affects the density of states. The surface effects could be attributed to a variable charge density at the surface of amorphous silicon films, and can cause changes of many orders of magnitude in the measured conductivity of gap cell samples.

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# Two-dimensional electron gas at a molecular beam epitaxial-grown, selectively doped, $In_{0.53}Ga_{0.47}As$-$In_{0.48}Al_{0.52}As$ interface

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We report the observation of a high-mobility, two-dimensional electron gas (2DEG) at the interface between a molecular beam epitaxial (MBE)-grown undoped $In_{0.53}Ga_{0.47}As$ layer and a subsequent layer of MBE-grown, Si-doped $In_{0.48}Al_{0.52}As$. Peak mobilities of $\sim$92 000 $cm^2\ V^{-1}\ s^{-1}$ have been observed at 4.2 K. From Hall and Shubnikov-de Haas studies we have found that the 2DEG can be characterized by $n_{ch} = 6\text{–}8\times10^{11}\ cm^{-2}$. In all cases we found two subbands to be occupied at $N_{ch} \gtrsim 4.5\times10^{11}\ cm^{-2}$.

PACS numbers: 73.60.Fw, 71.25.Jd

$In_{0.53}Ga_{0.47}As$ is a promising device material, having already found applications in the long-wavelength optical communications systems as a detector and emitter. In addition, the high bulk mobility (at room temperature) and the expected high saturation drift velocity, arising from the large $\Gamma$-$L$ separation in conduction band,[1,2] indicate that

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$In_xGa_{1-x}As$ may be attractive for high-speed field-effect transistor (FET) applications.

$In_{0.53}Ga_{0.47}As$ is closely lattice matched to $In_{0.52}Al_{0.48}As$ and InP so that high-quality heterojunctions between these ternaries may be grown strain-free on semi-insulating Fe-doped ⟨100⟩ InP substrates. As $In_{0.48}Al_{0.52}As$ has a larger band gap than $In_{0.53}Ga_{0.47}As$, and because it is expected that the excess, $\Delta E_g$, will be distributed between both conduction band ($\Delta E_c$) and valence band ($\Delta E_v$) discontinuities, doping of the $In_{0.48}Al_{0.52}As$ $n$ type should lead to an accumulation of electrons on the undoped $In_{0.53}Ga_{0.47}As$ side of the heterointerface. This type of behavior has led to extraordinary, low-temperature, two-dimensional electron gas (2DEG) mobilities in the analogous $Al_xGa_{1-x}As$-GaAs heterojunction structure.[3] In this letter we report the observation of a high-mobility 2DEG at the $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ interface of molecular beam epitaxial (MBE)-grown heterostructures.

A typical structure is shown in the inset of Fig. 1. A 1.5-$\mu$m-thick layer of unintentionally doped ($n \sim 0.5$–$1.0 \times 10^{16}$ cm$^{-3}$) $In_{0.53}Ga_{0.47}As$ is grown on a semi-insulating Fe-doped ⟨100⟩ InP substrate. This is followed by ~80 Å of undoped $In_{0.52}Al_{0.48}As$ and 1500 Å of Si-doped ($n \sim 0.3$–$1.0 \times 10^{18}$ cm$^{-3}$) $In_{0.52}Al_{0.48}As$. Following the $Al_xGa_{1-x}As$/GaAs case,[4] it is expected that carriers from the doped $In_yAl_{1-y}As$ will transfer to the conduction band of the $In_xGa_{1-x}As$ forming a 2DEG at the heterointerface. As before,[3,4] the undoped, 80-Å spacer of $In_yAl_{1-y}As$ aims to increase the separation between the electrons in the 2DEG and the donors in the highly doped region to decrease the ionized impurity scattering of the 2DEG, and to increase the low-temperature electron mobility. According to simple estimates, the thickness of the doped layers exceeds the expected depletion lengths in these layers. Consequently, contributions to the lateral conductance of the structure might be expected to come from electrons in these low-mobility regions. It will be shown in the following that parasitic contributions from such undepleted regions are of limited importance, especially at low temperatures.

Figure 1 shows typical Hall mobility $\mu_H$ and electron concentration results in the temperature range 1.75–300 K. At low temperature, mobilities are fairly constant, but a

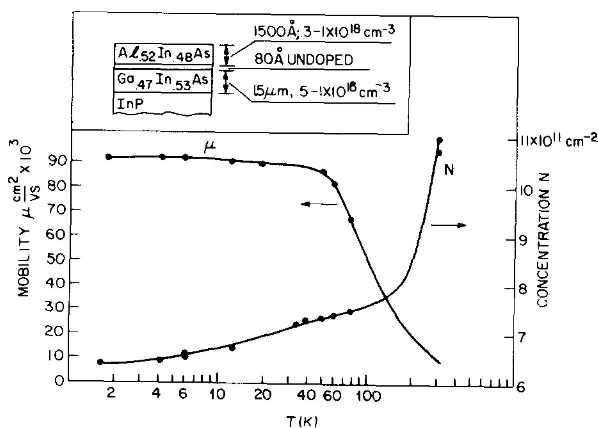


FIG. 1. Temperature dependence of Hall mobility and concentration in structure shown in inset.

marked drop occurs at $T \gtrsim 200$ °K. The mobilities in our samples were 88 000–93 000, 60 000–68 000, and 9 200–10 000 cm$^2$ V$^{-1}$ s$^{-1}$ $T = 4.2$, 77, and 300 K, respectively. These values are significantly higher than bulk mobilities in $In_xGa_{1-x}As$ at the same concentrations[5] suggesting the presence of an enhanced mobility 2DEG at the interface.

The concentration is essentially independent of temperature at low temperatures, but shows a substantial increase at $T \gtrsim 200$ K. Typical $N_H$ values are 0.8–1.2$\times 10^{12}$ cm$^{-2}$ at 77 K and 1–1.8$\times 10^{12}$ cm$^{-2}$ at 300 K. Temperature dependencies similar to those shown in Fig. 1 have been observed earlier in GaAs-$Al_xGa_{1-x}As$ superlattices and at single GaAs-$Al_xGa_{1-x}As$ interfaces and have been interpreted in terms of 2D conductance.[3,4]

We have used Shubnikov-de Haas (SdH) measurements to study further the electronic properties of these structures. In this way it is possible to prove, from the anisotropic behavior of the oscillation amplitude,[6] that there is in fact a 2DEG (presumed to be at the heterointerface) in the structure. Furthermore, detailed parameters of the 2DEG may be obtained from an analysis of the SdH oscillations allowing a more complete characterization of the electron gas to be achieved.

Figure 2 shows the SdH result for one of our samples ($\mu_H = 89\,000$ cm$^2$ V$^{-1}$ s$^{-1}$ at 4.2 K). Well developed oscillations in magnetoresistance are seen at very low magnetic fields ($H < 0.2$ T) for the $H$ perpendicular to the interface geometry, whereas for the $H$ parallel geometry oscillations do not develop at any magnetic field. This anisotropy is a manifestation of the presence of a two-dimensional electron system[7] in this sample. It is assumed that this 2DEG is at and on the $In_xGa_{1-x}As$ side of the heterointerface between $In_yAl_{1-y}As$ and $In_xGa_{1-x}As$.

The strong magnetoconductance $\sigma(H)$ effect observed in both orientations (at 4.2 K) obeys the classical formula

$$\frac{\sigma(H)}{\sigma_0} = \frac{1}{1 + \omega_e^2 \tau^2},$$

where $\omega_e = eH/m^*c$ and $\tau =$ the electron momentum relaxation time.

The relaxation time derived from this expression corresponds to a rather small mobility ~7–8$\times 10^3$ cm$^2$/Vs and certainly is not that expected of $\tau$ in the interface channel. It seems to be reasonable to ascribe this effect to the presence of electrons in undepleted layers of the structure that may exist in addition to the 2D electron gas in the channel. The decrease of the electron concentration as a function of temperature as shown in Fig. 1 can be explained by the effect of electron freeze-out in the low-mobility layers.

Two distinct oscillations are seen in SdH results (Fig. 2). These, we believe, originate from two, populated, bound states at the interface. Figure 3 presents the data reduction of the observed oscillations. Two linear dependences of Landau number $n$ vs $H^{-1}$ clearly demonstrate the concentration in channel $N_{ch}$:

$$N_{ch} = \frac{m^*}{\pi\hbar^2}(E_{F_0} + E_{F_1}) = \frac{e}{\pi\hbar c}(\alpha_1 + \alpha_2),$$

where $E_{F_0}$ and $E_{F_1}$ are Fermi levels of the lower and upper



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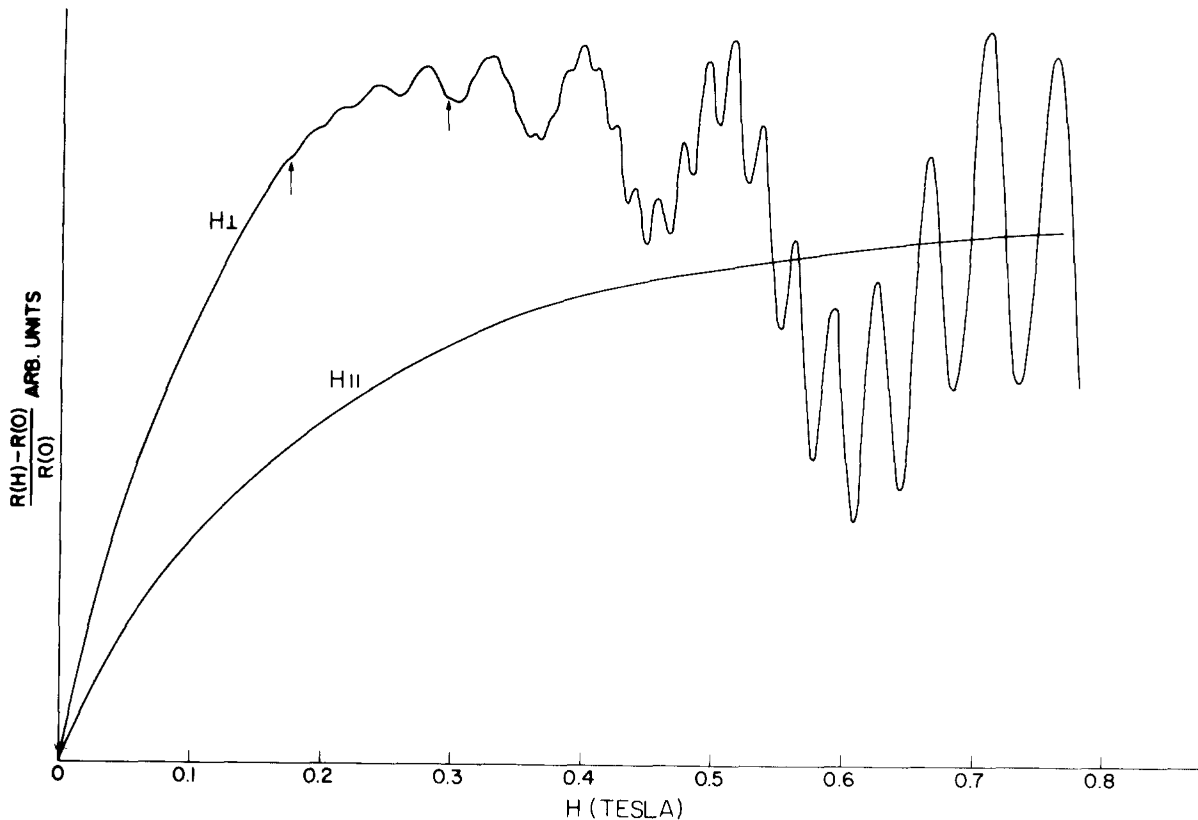


FIG. 2. SdH oscillations for the magnetic field perpendicular and parallel to the $In_xGa_{1-x}As$-$In_yAl_{1-y}As$ interface.

subbands, respectively, $\alpha_1$ and $\alpha_2$ are slopes of $dn/dH^{-1}$ for both dependences.

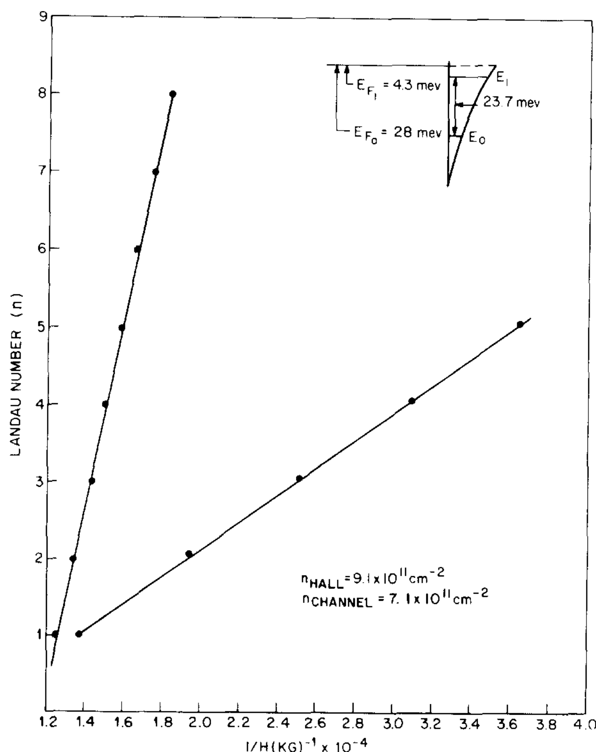


FIG. 3. Landau quantum number $n$ vs reciprocal field at maxima of magnetic oscillation. (Identification of Landau levels is arbitrary and does not refer to the quantum level numbering counted from the lowest energy state.) Inset shows the conditions in conduction band at the interface.

For a given sample we have $N_{ch} = 7.1 \times 10^{11}$ cm$^{-2}$ which is 80% of $N_H$. For all samples investigated, the ratio $N_{ch}/N_H$ was within 0.7–0.85 at $T = 4.2$–77 K. If we take into account that mobility in the channel is at least 5–10 times higher than in the undepleted layers, one can suggest that at low temperatures ($\lesssim 77$ K) the conductance of the structure is essentially controlled by the channel.

From the temperature dependence of the SdH oscillation amplitude it is possible to extract an electron effective mass.[8] We find $m^* \approx 0.0485$–$0.051\ m_0$, significantly higher than in the bulk ($\sim 0.04/m_0$).[9] Using $m^* = 0.05 m_0$, a subband separation of 23.7 meV and Fermi levels $E_{F_0} = 28$ meV and $E_{F_1} = 4.3$ meV were derived (see inset in Fig. 3). Estimates show that second subband starts to be occupied at concentration $N \gtrsim 4.5 \times 10^{11}$ cm$^{-2}$.

Finally, a marked photoconductivity effect has been observed at low temperatures ($\lesssim 77$ K) both in the Hall measurements and from a change in period of the SdH oscillations. After momentary illumination, the concentration in the channel increases by 5–15% (depending on initial concentration and temperature). A similar photoeffect has been observed earlier at the $GaAs/Al_xGa_{1-x}As$ interface and has been interpreted as a transfer of photoelectrons into the channel.[7]

In conclusion, our experiments demonstrate the presence of a high electron-mobility 2DEG at $In_{0.53}Ga_{0.47}As$-$In_{0.48}Al_{0.52}As$ interface. We believe that it is possible to significantly increase the mobility values that we currently observe. The probable limitation (compare with $GaAs/Al_xGa_{1-x}As$ interface) comes from alloy scattering which is of importance in $In_xGa_{1-x}As$. According to Ref.



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10, where the best match of experimental and theoretical results is presented, alloy scattering limits the mobility at $3\times10^5$ cm$^2$ V$^{-1}$ s$^{-1}$ (4.2 K), $1.8\times10^5$ cm$^2$ V$^{-1}$ s$^{-1}$ (77 K), and $2\times10^4$ cm$^2$ V$^{-1}$ s$^{-1}$ (300 K). Therefore, at low temperature, one can reach mobility values in $In_xGa_{1-x}As$ layers that are close to the highest so far obtained for the GaAs/$Al_xGa_{1-x}As$ interface. Taking into account the earlier mentioned high-peak drift velocity in $In_xGa_{1-x}As$, it is possible to conclude that the present structure looks very attractive for high-speed FET applications.

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# Transport in modulation-doped structures ($Al_xGa_{1-x}As$/GaAs) and correlations with Monte Carlo calculations (GaAs)

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Electron velocity and mobility versus electric field measurements were made in $Al_xGa_{1-x}As$/GaAs modulation-doped structures in an electric field range of 0–2 kV/cm and in a temperature range of 77–300 K. The electron velocities obtained at 2 kV/cm were $1.7\times10^7$ cm/s at 300 K and $2.24\times10^7$ cm/s at 77 K. The velocity-field and mobility-field characteristics obtained were in very good agreement with Monte Carlo results for undoped GaAs, suggesting that existing Monte Carlo calculations are capable of predicting transport in $Al_xGa_{1-x}As$/GaAs modulation-doped structures. An ideal modulation-doped structure can thus be assumed to exhibit transport properties identical to that of undoped GaAs. The advantage of modulation doping is the ability to place $7\times10^{11}$ cm$^{-2}$ electrons at the heterointerface for current conduction for devices, while avoiding all the adverse effects of impurity scattering.

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Modulation-doped (MD) (Al,Ga)As/GaAs heterojunctions have been the focus of a great deal of attention since the first experimental demonstration of mobility enhancement in 1978.[1] Electrons from the doped $Al_xGa_{1-x}As$ diffuse into the undoped GaAs, leading to the separation of the ionized donors from the electrons. In addition, Coulomb scattering by the remote donors can be virtually eliminated by incorporating a thin undoped region of (Al,Ga)As at the interface.[2] The factors limiting mobility then are the properties of GaAs and the smoothness of the interface.[3]

Extremely high mobilities obtained in MD structures, particularly at cryogenic temperatures, made it attractive to consider them for high-speed logic[4–6] field-effect transistors (FET's) operating in the constant mobility regime. A velocity larger than that in doped GaAs was also predicted, though not confirmed prior to this report, which can lead to high-performance short-channel FET's.[7]

In this letter, data are presented which demonstrate transport in modulation-doped (Al,Ga)As/GaAs heterostructures to be very nearly predictable by Monte Carlo calculations[8,9] done for undoped bulk GaAs. Both show that velocities greater than $2\times10^7$ cm/s are obtainable at 77 K and a field strength of 2 kV/cm. This compares with an effective velocity of $1\times10^7$ cm/s measured in doped GaAs at 300 K and 2 kV/cm.[10] The electron velocity of such heavily doped GaAs is essentially independent of temperature.

The structures were grown on Cr-doped substrates by molecular beam epitaxy and the details of the growth procedure were reported elsewhere.[11] The structures consisted of a 1.0-$\mu$m GaAs buffer layer, a Si-doped $Al_xGa_{1-x}As$ layer ($n\approx7\times10^{17}$ cm$^{-3}$ and 0.15 $\mu$m in samples A through D, 600 Å thick in sample E), and 200-Å cap layer of GaAs. In samples A, B, and C, the GaAs buffer layer was doped to electron concentration $N_B$ of between $1\times10^{16}$ and $1\times10^{17}$

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