Electron mobilities in modulation-doped semiconductor heterojunction superlattices

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GaAs-$Al_xGa_{1-x}As$ superlattice structures in which electron mobilities exceed those of otherwise equivalent epitaxial GaAs as well as the Brooks-Herring predictions near room temperature and at very low temperatures are reported. This new behavior is achieved via a modulation-doping technique that spatially separates conduction electrons and their parent donor impurity atoms, thereby reducing the influence of ionized and neutral impurity scattering on the electron motion.

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Synthetic semiconductor superlattice structures are of both fundamental and technological interest. Most suggestions concerning the growth of such structures focus on either a multilayer heterojunction arrangement[1,2,4] or a periodic alternation of the doping of only one semiconductor to form a series of homojunctions.[3–5] Molecular-beam epitaxy (MBE) is known[6] to produce atomically smooth layers and to allow very precise control over grown layer thickness. In particular, these features have been utilized in the production of multilayer heterojunction superlattices of GaAs-$Al_xGa_{1-x}As$ [1,2] and other semiconductor combinations.[7,8] Layer thicknesses on the order of atomic dimensions have been routinely[9] achieved. Typical unintentionally doped GaAs-$Al_xGa_{1-x}As$ structures are thought to be lightly p type,[1] whereas deliberate uniform doping can produce superlattices with $n \sim 10^{18}$ cm^{-3}.[10–12] In this doping range, mobilities significantly greater than $\mu \sim 10^3$ cm^{2}V^{-1}sec^{-1} are difficult to achieve. Such mobilities, which are considerably below the Brooks-Herring-Dingle predictions[13] for uncompensated GaAs at this concentration, severely limit the usefulness of these structures.

In this letter, we wish to report the growth and properties of *heterojunction* superlattices of GaAs-$Al_xGa_{1-x}As$ in which the independent notion of *modulation doping* is incorporated. Resultant Hall mobilities (300 K) for electrons are larger than any yet reported for either uniformly doped GaAs-$Al_xGa_{1-x}As$ superlattices, equivalently doped MBE-grown bulk GaAs, or equivalently doped GaAs grown by other means. Moreover, the 300 K mobilities are usually greater than the upper limit predicted by the Brooks-Herring-Dingle theories of electron mobility in bulk n-type GaAs. At temperatures below 50 K a dramatic increase over the mobilities of uniformly doped n-type heterojunction superlattices and bulk GaAs of equivalent electron concentration is obtained.

The structures were grown in an MBE system described earlier[1,9] with the modification that a silicon doping source, which could be abruptly initiated or terminated, was included. Uniformly doped multilayer heterojunctions were grown with a calibrated Si beam impinging continuously on the sample. These structures are n type with room-temperature mobilities in the 1000–2500-cm^{2}V^{-1}sec^{-1} range. Depending on the doping level, mobilities are either essentially temperature independent ($n \sim 10^{17}$–10^{18} cm^{-3}) or else they decrease strongly on cooling ($n < 10^{17}$ cm^{-3}).

Modulated doping is achieved by synchronization of the Si and Al source fluxes so that only the $Al_xGa_{1-x}As$ layers are deliberately doped with Si impurities. In a second version, the Si beam is shuttered in such a way that up to 60 Å of each side of every $Al_xGa_{1-x}As$ layer are not intentionally doped, thus keeping the Si dopant away from the interface region. If, as we believe, Si diffusion is negligible at the growth temperature of ~600 °C, then in each structure the GaAs layers will contain only unintentional background impurities (10^{14}–10^{15}-cm^{-3} range).

Figure 1 presents a model for the conduction band edge structure of a uniformly doped (UD) and a modulation-doped (MD) superlattice. Si donors are distributed according to the appropriate doping method. Typically $x \simeq 0.3$ in $Al_xGa_{1-x}As$, leading to $\Delta E_c \simeq 300$ meV. The binding energy of isolated Si donors in bulk GaAs is

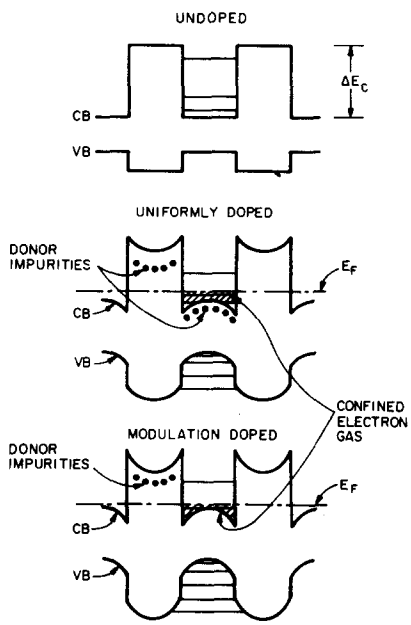

FIG. 1. Energy-band diagrams for n-doped and undoped GaAs-$Al_xGa_{1-x}As$ superlattices.

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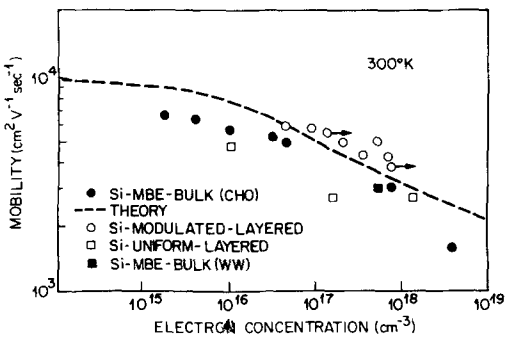

FIG. 2. 300 K mobilities of a range of Si-doped GaAs and Si-doped GaAs-$Al_xGa_{1-x}As$ superlattices. The filled circles and the theory [Brookes-Herring, $(N^+ + N^-)/n = 1$] are taken from Ref. 6. The horizontal arrows show electron concentration changes discussed in the text.

$E_{D,Si}^{GaAs} \sim 6$ meV, whereas in $Al_xGa_{1-x}As$ it has been suggested that Si can introduce a dominant deep donor with $E_D \sim 100$ meV or larger. Lang *et al.*[14] believe that this deep donor merges with the conduction band at $x \lesssim 0.35$ and so, in the present case, we expect that $\Delta E_c \gg E_D$.[15] Since the GaAs conduction band edge lies lower in energy than the $Al_xGa_{1-x}As$ donor states, electrons from the donors will move into the GaAs regions. For both UD and MD structures the $Al_xGa_{1-x}As$ regions are depleted in order to satisfy the requirement of a continuous Fermi level throughout each superlattice, which in turn leads to appreciable band bending (which is impurity-concentration and layer-thickness dependent). This is depicted in a qualitative manner in Fig. 1. In both UD and MD superlattice structures the carriers confined to the GaAs layer will form a pseudo-two-dimensional electron gas (2DEG).

The most important feature of the MD structure is that essentially all of the mobile carriers (electrons confined to the GaAs layer) and their parent donor impurities (in the $Al_xGa_{1-x}As$ layer) are spatially separated from each other in an irreversible manner. Thus the electron density in the GaAs channel may greatly exceed the density of the unintentionally present (neutral and ionized) impurity scattering centers in the channel, leading to considerable change in mobility behavior in the temperature and carrier density regimes where impurity scattering mechanisms are important. In many respects the situation resembles that in a Si-MOSFET where the 2DEG concentration is also independent of the doping level in the channel. To a much smaller degree, mobility enhancement could also occur in UD structures, although in the range of UD superlattices that we have studied, mobility enhancement has not been observed. A periodic doping of a single semiconductor material to form a chain of $(nipi)_m$ regions[3-5] would have the opposite effect to that of modulation doping, namely, the mobile electrons (holes) would be restrained to the *same* spatial region as their parent donor (acceptor) impurity. Enhanced mobility behavior is not anticipated.

Figure 2 compares 300 K mobilities of MBE-grown GaAs samples of differing carrier concentration with those of UD and MD GaAs-$Al_xGa_{1-x}As$ superlattices. The Hall mobilities in the MD structures are as much as a factor of 2 greater than the mobilities of electrons in UD superlattices or in GaAs of equivalent electron concentration. If essentially all of the electrons contributing to the conduction process are considered to be in the GaAs channels,[16] then the mobility is that of material containing almost twice as many carriers as derived using the total superlattice thickness-"bulk" GaAs approach. The resultant shift is shown in the data of Fig. 2. Variation of the layer thickness in the range 100—450 Å appears to have only a minor influence on these room-temperature mobilities.

Perhaps the most dramatic influence of modulation doping is in the temperature dependence of the mobility. In Fig. 3 we compare the mobility of a MD superlattice ($n \sim 5 \times 10^{16}$ cm^{-3}), which is typical of MD structures, with a range of data from UD structures and an MBE GaAs sample. The mobility behavior of the latter in the < 100 K range is mainly attributed to ionized impurity scattering.[13] In this regime the mobility should follow a $T^{3/2}$ law.[13,17] The UD samples and the MBE-grown GaAs do show a $T^{3/2}$ behavior although a good quantitative fit to the appropriate expression (including screening) using reasonable parameters is only possible for the bulk sample. In contrast, the MD samples should show strongly modified impurity scattering since the Coulomb interaction with ionized impurities responsible for the $T^{3/2}$ scattering should be greatly reduced by the segregation of carriers and impurities. This yields a more metallic-like behavior, the mobilities showing a smooth increase with decreasing temperature. A detailed understanding of the mobility behavior in the 2DEG in these structures in terms of the modified two-dimensional impurity-scattering mechanism has not yet been achieved. From the preliminary information that we have, it appears that both UD and MD structures will require a detailed, but different treatment.

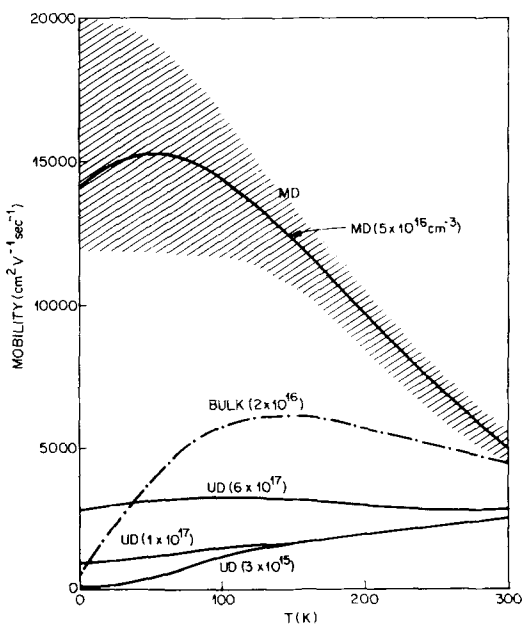

FIG. 3. Electron mobility versus temperature for bulk GaAs GaAs and several UD and MD superlattices. The crosshatched region includes most of the MD data.

In the doping range under consideration, $n > 10^{16}$ cm^{-3}, carrier freeze-out is not seen in any of UD or MD superlattices or in the MBE-grown bulk GaAs. This means that in MD superlattices one may expect electron concentrations as high as 10^{18} cm^{-3} with mobilities of at least 10^4 cm^2 V^{-1} sec^{-1} at liquid-helium temperatures. These low-temperature mobilities compare very favorably with those obtained at He temperatures from the very best CVD-grown GaAs [13,18] in which the carrier density is as much as 10^{-5} smaller. A range of studies on these new structures is in progress. As an example of the low-temperature behavior of the 2DEG, we note that highly anisotropic oscillatory magnetoresistance behavior (Shubnikov–de Haas effect) has been seen at fields as low as 1 T, which is very much lower than data previously reported[11] for similar UD structures.

In summary, we have described MBE-grown, MD heterojunction superlattices of GaAs-$Al_xGa_{1-x}As$ in which low-temperature and room-temperature electron mobilities can be significantly higher than those in equivalent GaAs material grown in other ways. At room temperature this may be valuable for a range of device structures, whereas, at temperatures below ~50 K, mobilities of $\gtrsim 10^4$ cm^2 V^{-1} sec^{-1} and electron densities of up to ~10^{18} cm^{-3} access a new range of fundamental and device possibilities.

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[15]Hall data from a bulk Si-doped $Al_{0.26}Ga_{0.74}As$ layer indicates a deep level at $E_D \sim 60$ meV as well as what appears to be a temperature-independent electron concentration of $\sim 1.5 \times 10^{16}$ cm^{-3} at low temperatures.
[16]Mobilities in MBE-grown $Al_xGa_{1-x}As$ are low. In particular, the sample mentioned in Ref. 15 has a maximum mobility of $\mu \simeq 800$ cm^2 V^{-1} sec^{-1} at room temperature which falls to $\mu \sim 10$ cm^2 V^{-1} sec^{-1} at 4.2 K. In the superlattices, any carriers remaining in the $Al_xGa_{1-x}As$ layer will make an insignificant contribution to the conductivity, especially at low temperatures.
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Angle-resolved photoemission measurements of band discontinuities in the GaAs-Ge heterojunction[a)]

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The conduction- and valence-band discontinuities for the (110) GaAs-Ge heterojunction have been measured as $\Delta E_c = 0.50$ eV and $\Delta E_v = 0.25$ eV by the angle-resolved ultraviolet photoemission (ARUPS) technique. These values are in good agreement with the theoretical predictions of Pickett *et al.*

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During the past ten years, much effort has been devoted to understanding the physical properties of Schottky barriers and heterojunctions.[1] In both systems, the main effects originate at the interface; for example, it is well known that Schottky-barrier heights, as measured by capacitance voltage (C-V) or current-voltage (I-V) characteristics, are nearly independent of the metal's work function for covalent semiconductor-metal pairs. Several theoretical models have been suggested to account for this pinning of the Fermi energy (E_f).[2–4] Recent results obtained with surface-sensitive techniques such as ultraviolet photoelectron spectroscopy (UPS),[5,6] partial yield spectroscopy,[7] and electron

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