Electron mobilities in modulation-doped semiconductor heterojunction superlattices

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GaAs-AlGaAsAs 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 of, or a periodic alternation of the doping of only one semiconductor to form a series of homojunctions. Molecular-beam epitaxy (MBE) is known 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-AlGaAs and other semiconductor combinations. Layer thicknesses on the order of atomic dimensions have been routinely achieved. Typical unintentionally doped GaAs-AlGaAs structures are thought to belightly p type, whereas deliberate uniform doping can produce superlattices with n ≈ 10^18 cm^-3. In this doping range, mobilities significantly greater than μ ≈ 10^6 cm^2/V·sec are difficult to achieve. Such mobilities, which are considerably below the Brooks-Herring-Dingle predictions 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-AlGaAs 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-AlGaAs 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 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·sec range. Depending on the doping level, mobilities are either essentially temperature independent (n ≈ 10^15–10^16 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 AlGaAs 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 AlGaAs 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).

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 = 0.3 in AlGaAs, leading to ΔE = 300 meV. The binding energy of isolated Si donors in bulk GaAs is

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FIG. 1. Energy-band diagrams for n-doped and undoped GaAs-AlGaAs superlattices.
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, 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 ($n = 5 \times 10^{16}$ 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. In this regime the mobility should follow a $T^{3/2}$ law. 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.

![Graph of mobility vs. temperature for bulk GaAs and MD structures](image-url)
In the doping range under consideration, \( n > 10^{18} \text{ cm}^{-3} \), 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 \( 10^{19} \text{ cm}^{-3} \) with mobilities of at least \( 10^{6} \text{ cm}^{2}\text{V}^{-1}\text{sec}^{-1} \) at liquid-helium temperatures. These low-temperature mobilities compare very favorably with those obtained at He temperatures from the very best CVD-grown GaAs in which the carrier density is as much as \( 10^{8} \) 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\(^1\) for similar UD structures.

In summary, we have described MBE-grown, MD heterojunction superlattices of GaAs-Al\(_{x}\)Ga\(_{1-x}\)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 \( \sim 50 \text{ K} \), mobilities of \( \geq 10^{6} \text{ cm}^{2}\text{V}^{-1}\text{sec}^{-1} \) and electron densities of up to \( \sim 10^{11} \text{ cm}^{-3} \) access a new range of fundamental and device possibilities.

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Hall data from a bulk Si-doped Al\(_{x}\)Ga\(_{1-x}\)As layer indicates a deep level at \( E_D \sim 60 \text{ meV} \) as well as what appears to be a temperature-independent electron concentration of \( \sim 1.5 \times 10^{16} \text{ cm}^{-3} \) at low temperatures.
Mobilities in MBE-grown Al\(_{x}\)Ga\(_{1-x}\)As are low. In particular, the sample mentioned in Ref. 15 has a maximum mobility of \( \mu \geq 800 \text{ cm}^{2}\text{V}^{-1}\text{sec}^{-1} \) at room temperature which falls to \( \mu \sim 10 \text{ cm}^{2}\text{V}^{-1}\text{sec}^{-1} \) at 4.2 K. In the superlattices, any carriers remaining in the Al\(_{x}\)Ga\(_{1-x}\)As layer will make an insignificant contribution to the conductivity, especially at low temperatures.

**Angle-resolved photoemission measurements of band discontinuities in the GaAs-Ge heterojunction\(^{\text{a}}\)**

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The conduction- and valence-band discontinuities for the (110) GaAs-Ge heterojunction have been measured as \( \Delta E_c = 0.50 \text{ eV} \) and \( \Delta E_v = 0.25 \text{ eV} \) 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 (\( E_F \)).\(^{\text{2-4}}\) Recent results obtained with surface-sensitive techniques such as ultraviolet photoelectron spectroscopy (UPS),\(^{\text{5-6}}\) partial yield spectroscopy,\(^{\text{7}}\) and electron spectroscopy for chemical analysis (ESCA),\(^{\text{8}}\) have shown that these interfaces are of great interest for understanding the behavior of materials at interfaces. The results presented here are expected to be useful in understanding the results of these experiments.

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