ELECTRONIC PROPERTIES OF MODULATION-DOPED GaAs-$A\ell_xGa_{1-x}As$ SUPERLATTICES

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High-mobility GaAs-AℓGaAs superlattice structures, grown via a new modulation-doping technique, are reported. Mobilities exceed the Brooks-Herring predictions for equivalently-doped bulk GaAs at room temperature and at very low temperatures. Oscillatory magnetoresistance data demonstrate the system to be a high-mobility 2-D layered electron-gas and give indications of the 2-D subband energy level scheme. A novel persistent-photoconductive effect allows continuous electron-density change over a finite range.

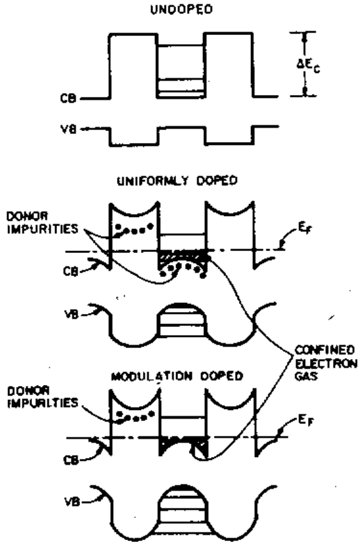

Fig. 1 Band edge variation of undoped and n-doped GaAs-AℓGaAs superlattices.

Semiconductor superlattices are grown using Molecular Beam Epitaxy (MBE).[1] GaAs-AℓGaAs superlattices are most extensively studied and have been shown to contain virtually interface state free, sharp transitions from one material to the other, resulting in abrupt steps in the band-edge energy.[2] (See Fig. 1 top.) For transport studies[3] carriers have been introduced by uniformly doping the complete structure during MBE-deposition (Fig. 1 center). Thus conductivity is thermally activated (at low concentration) or results from impurity-band formation and subsequent overlap with the band edge of the host material (high concentration). Electron mobilities higher than 1250 $cm^2 V^{-1} sec^{-1}$ have not been reported.[3]

We introduce a modulation-doping (MD) technique for semiconductor superlattices that results in a qualitatively different mechanism of carrier introduction. MD is achieved during MBE growth by restricting (Si)-donors to the AℓGaAs layers of the superlattice (Fig. 1 bottom), leaving the GaAs layers undoped (p-type $10^{15}cm^{-3}$). In order to maintain a constant Fermi level throughout the sample, Si-donors in the AℓGaAs barrier ionize, transferring their electrons to the GaAs conduction-band channel which is $\Delta E_C \approx$ 300 meV lower in energy. Thus the parent impurities become spatially separated from the conducting medium. Impurity scattering for carrier motion along the channel (in the GaAs plane) is greatly reduced. Although the charge separation leads to appreciable band bending, the carriers remain confined to the GaAs-layer and form a high-mobility 2-D layered electron-gas.

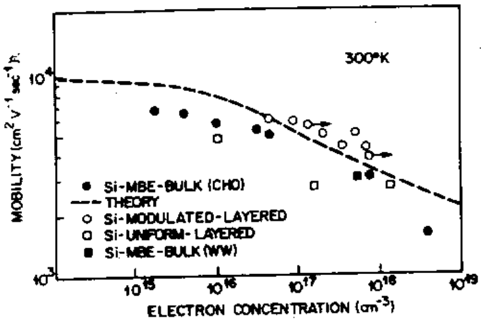

Fig. 2 300K-mobilities of a range of Si-doped GaAs-AℓGaAs superlattices. Filled circles and theory (---) taken from Ref. 1.

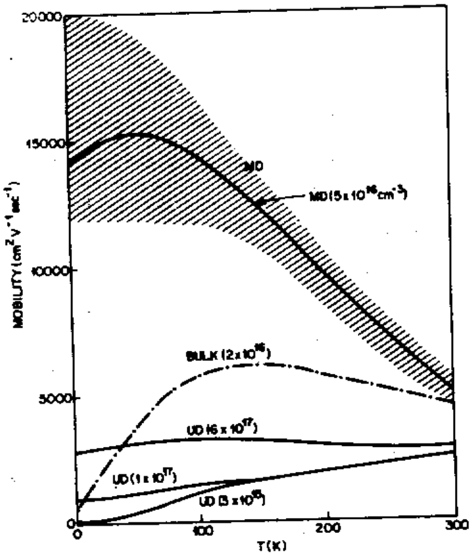

Fig. 3 Mobilities versus temperature for Si-doped samples. Cross-hatched region includes most of the MD-data.

The room-temperature mobility of these MD-structures (Fig. 2) does not only exceed the electron mobilities of uniformly-doped (UD)-superlattices and bulk GaAs of equivalent electron-concentration but even exceeds the prediction given by the Brooks-Herring theory (Fig. 2). This mobility increase is most probably related to the reduced importance of impurity scattering. Fig. 3 shows the temperature dependence of the electron mobility. The mobility of UD-superlattices remains

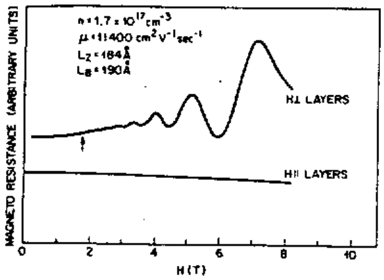

Fig. 4 Oscillatory magnetoresistance versus field for a MD-structure for H-field perpendicular to (H⊥) and in the plane of (H||) the layers.

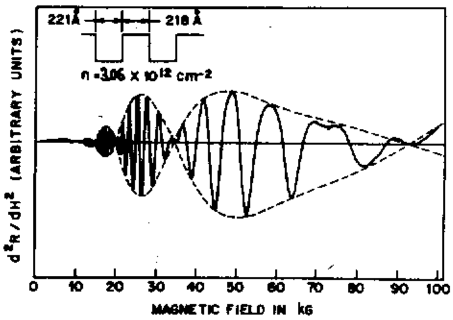

Fig. 5 Interference effect in oscillatory magnetoresistance (H⊥ to layers) indicates population of 2 subbands.

under 3000 $cm^2V^{-1}sec^{-1}$ over the total temperature range and the bulk sample shown exhibits a reduction in mobility on approaching low temperatures. The mobility of MD-samples, on the other hand, exceeds that of all equivalently-doped GaAs materials at room temperature and below 50K[4] and shows low-temperature values as high as 20000 $cm^2V^{-1}sec^{-1}$. Therefore, MD-structures are particularly interesting for low-temperature transport studies on a 2-D layered electron-gas.

Fig. 4 demonstrates the 2-dimensionality of our MD structures via the anisotropy of the Shubnikov de Haas (SdH) effect.[5] SdH-oscillations, heretofore seen in GaAs-AℓGaAs superlattices only in high magnetic fields,[3] appear at ∿ 20 kG (arrow Fig. 4). This allows us to study extensively the level scheme of the bound states of the electrostatically perturbed GaAs-potential well. Fig. 5 shows the second derivative of the SdH-oscillations of a sample with 221 Å wells. The evident beating effect results from interference of two SdH-oscillations of slightly different period and, after data reduction, demonstrates clearly the occupation of 2 subband levels having a separation of 8.6 meV.

Finally, in Fig. 6, we present evidence of a new persistent-photoconductive effect occuring in most of our samples. The carrier concentration in the GaAs channel

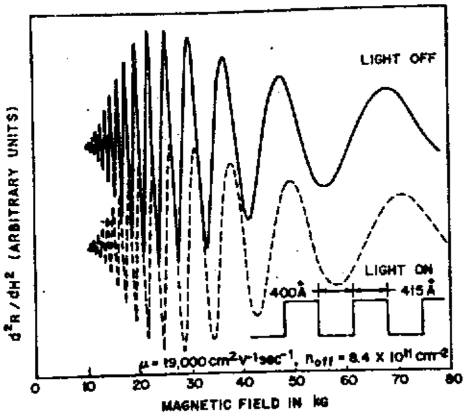

Fig. 6 Oscillatory magnetoresistance demonstrates persistent photoconductive effect. Carrier density is increased by 6% due to light exposure.

(proportional to the period of the SdH-oscillations) can be varied by light exposure (typically 100 sec for saturation). The carrier increase is persistent at low temperatures, can be varied continuously (exposure time), and is reversible by heating the sample to 100 K or more. The origin of this photoeffect, which allows us to study various properties of the layered electron-gas over a finite range of densities, is probably related to a DX-like center[6] in the AℓGaAs barrier.

In summary, we report on a high-mobility 2-D electron-gas in GaAs-A GaAs heterojunction superlattices achieved by a novel modulation-doping technique. The increased room-temperature mobility and the high low-temperature mobility suggest device possibilities as well as detailed studies of the properties of a 2-dimensional layered electron-gas. We wish to thank L. Kopf, M. D. Sturge, V.Narayanamurti, and M.B. Panish for their help.

References

1. A Y Cho and J R Arthur in Prog. in Solid State Chem Vol 10, G Somorjai and J McCaldin eds, Pergamon Press (1975), p 147.
2. For a review see: R Dingle in Festkorperprobleme (Adv. in Sol. St. Phys.) Vol XV, H J Queisser ed, Pergamon-Vieweg, Braunschweig (1975), p 21.
3. L L Chang, H Sakaki, C A Chang and L Esaki, Phys. Rev. Lett. 38, 1489 (1977).
4. For other GaAs bulk data see e.g.: G E Stillman and C.M. Wolfe, Thin Solid Films, 31, 69)1976)
5. F Stern and W E Howard, Phys. Rev. 163, 816 (1967).
6. R J. Nelson, Appl. Phys. Lett. 31, 351 (1977); D V Lang and R A Logan, Phys. Rev. Lett. 39, 635 (1977).