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MODULATION DOPING OF SEMICONDUCTOR SUPERLATTICES AND INTERFACES

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A modulation-doping technique for semiconductor heterojunction superlattices is described. Spatially controlled impurity incorporation enhances strongly the carrier mobility in the plane of the layered material. Mobilities exceed those of equivalent epitaxial bulk-material over wide ranges of temperature. Modulation-doping is applied to superlattices and single heterojunctions. We present a review on the physics of modulation-doped GaAs-(AlGa)As structures emphasizing recent experiments.

The physics of semiconductor heterojunction superlattices, though being one of the younger branches of semiconductor physics, has come a long way [1,2]. The reports presented biannually at this conference bear witness of the successive achievements of this fast-moving field [3,7]. Having been regarded earlier as the esoteric corner of a few, the production and analysis of semiconductor superlattices nowadays is pursued in a rapidly increasing number of laboratories. This development went hand in hand with the proliferation of Molecular Beam Epitaxy (MBE) [1,8], the relatively elaborate crystal growth technique which up to now is the only growth technique that has provided sufficient control over the growth process to allow for manipulation on the atomic scale.

Though, from the beginning, device interests were a strong reason for research in the superlattice field [9], it was not until very recently that a line of research in superlattice transport [7,10-13] turned out to be very promising for applications and first reports of successful device implementations are now available [14].

The underlying concept of this development is a novel doping technique called modulation-doping (MD) [7,10-13] which overcame in two dimensions the low carrier mobility, one of the most serious difficulties of earlier superlattice transport research. It turns out that over a wide range of doping concentration, mobilities achievable in modulation-doped (MD) superlattices are even superior to those of equivalently doped epitaxial bulk material at temperatures which are particularly interesting from the point of view of basic research as well as device studies.

Since the first announcement of modulation-doping at the 14th International Conference in Edinburgh [7], initial studies have been extended and a variety of other tools have been applied to these structures.

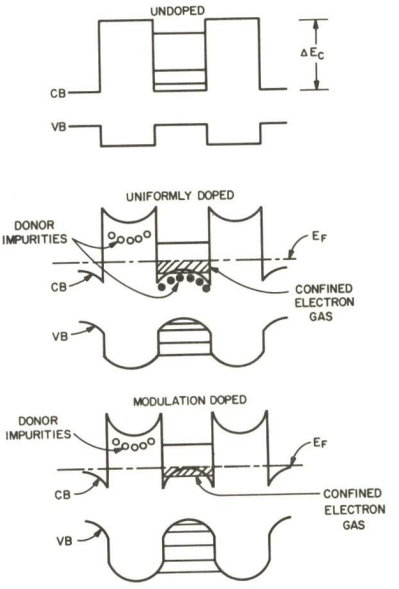

Fig. 1 Schematic energy diagram for undoped and n-doped GaAs-(AlGa)As superlattices

Modulation-doping has been applied to single heterojunction interfaces in MBE [11,12] and proved to be successful even in LPE (Liquid Phase Epitaxy) [15]. Equivalent p-type structures with strongly improved hole mobilities have been demonstrated [16]. Far-infrared (FIR) cyclotron resonance[11,12] and most recently light-scattering experiments[17,18] have been successfully performed on the two-dimensional electron gas (2DEG) present in these materials. The first observation of magneto-phonon resonance in a two-dimensional electronic system was reported for MD structures [19]. Theoretical work supported the initial explanation for the improved transport properties [20,21], led to a more profound understanding of the process and suggested new lines of research [22]. This report will briefly review the recent developments.

Superlattices

MBE-grown GaAs-(AlGa)As multilayers are the most extensively studied realization of the superlattice concept [1,2]. Differences in band gaps and chemical potentials between both materials lead in multilayered GaAs-(AlGa)As structures to periodic abrupt variations of the conduction and valence band edges with typical step heights of $\sim$ 100 meV, depending on the Al concentration of (AlGa)As (see Fig. (1)). Typical periods being on the order of 10^2 Å, these superlattices exhibit discrete energy levels.

The standard sample preparation for steady state transport measurement involves doping of the semiconductor material. Previously doping of superlattices was accomplished during high vacuum growth by having a molecular beam of a suitable dopant continuously impinging[3,23,24] onto the sample (UD, uniform-doping). Consequently, impurities were introduced into all layers, see Fig. (1). Modulation-doping[7,10-13] restricts impurity incorporation to the wide gap material ((AlGa)As:Si, 10^{17}-10^{18} cm^{-3}) by periodically chopping the dopant beam synchronously with the Al-molecular beam, thereby leaving the narrow gap material (GaAs) essentially free of impurities ($\sim 10^{15}$ cm^{-3}), see Fig. (1). Obviously, impurity incorporation can be further restricted to the center region of (AlGa)As.

To fulfill the requirements of a constant Fermi energy throughout the sample, electrons transfer from the (AlGa)As layers into the GaAs layers in the UD as well as in the MD case, leading to considerable band bending. Carrier transport along the layers occurs almost exclusively within the degenerate 2DEG of the GaAs layers.

The strong improvement of transport properties achieved by spatial separation of electrons from their parent impurities is demonstrated in Fig. (2) via a comparison of Hall-mobilities [7,10]. The data are representative figures. Depending on layer thickness, Al-contents and doping concentration, the actual mobility values vary. There is a general trend to higher mobilities for thicker GaAs layers and for increased distance of dopant from the interface. However, consider-

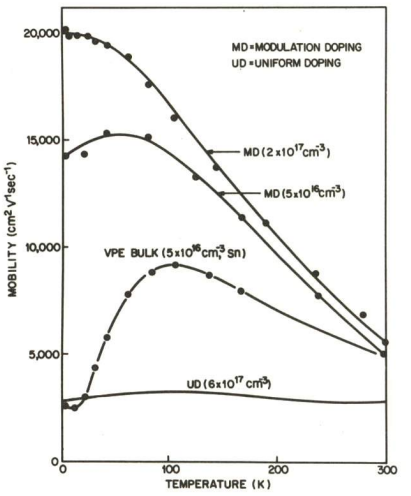

Fig. 2 Comparison of the temperature dependent mobility of various bulk GaAs and GaAs-(AlGa)As superlattice materials: VPE-data Ref. [25]

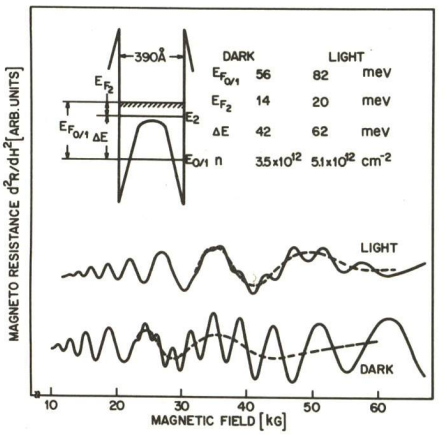

Fig. 3 SdH-data of a typical MD-superlattice: Field normal to the layers. The inset shows the conduction band edge

able statistical fluctuations in the data from a variety of samples do not allow determination of the exact dependence of mobility on those parameters. Nevertheless, low temperature Hall-mobilities of more than 20,000 $cm^2/Vsec$ have been achieved repeatedly.

The superior transport properties of MD-material with respect to UD-material is strongly supported by theoretical calculations [20,21]. The predominant scattering mechanism in MD-structures remains scattering by the long range Coulomb potential of the ionized impurities in the (AlGa)As barriers. However, yet higher mobilities are theoretically predicted.

From the confinement of carriers to the GaAs layers with strongly deformed bands, we can expect a quasi two-dimensional behavior of MD-structures with a sequence of bound states which strongly deviates from the simple level scheme of a square well [2]. Oscillatory magnetoresistance (Shubnikov-deHaas effect, SdH) is a convenient tool to probe these predictions. Figure (3) shows, as an example, the SdH-result for a wide well MD-structure. Two distinct oscillations arising from two populated bound states are well developed. Moreover, from the onset of oscillation we find the electrons in the upper band to be approximately 3 times more mobile than those of the lower subband. A simple numerical calculation predicts for $n=3.5\times10^{12}$ cm^{-2} a doubly degenerate ground state 38 meV below the first excited state, in good agreement with the experimental value (see inset Fig. (3)). Recent self-consistent calculations on the subband structure of MD-superlattices [26] have been in excellent agreement with our earlier experimental results. The strongly differing mobilities of both states we attribute to very different proximity of the bound states to the ionized impurities in the (AlGa)As barrier.

Figure (3) shows yet another interesting feature of doped-GaAs-(AlGa)As superlattices. Short-time illumination with near infrared (or higher energetic) light has an appreciable effect on the carrier concentration [7,10]. The density increase persists in the dark. It is attributed to the persistent ionization of a deep trap in the (AlGa)As barriers which has been earlier identified in bulk material

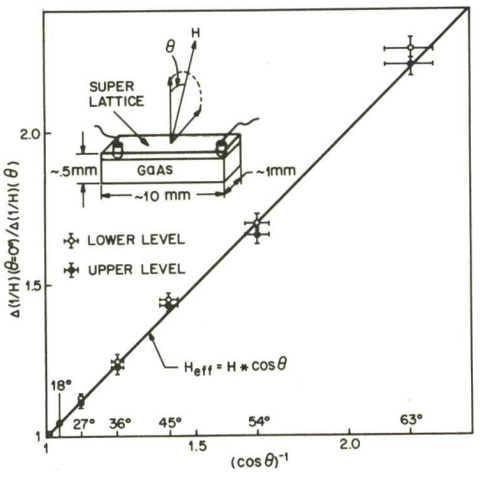

Fig. 4 Angular dependence of SdH-data of sample from Fig. (3): Straight line shows theoretical result for a 2DEG

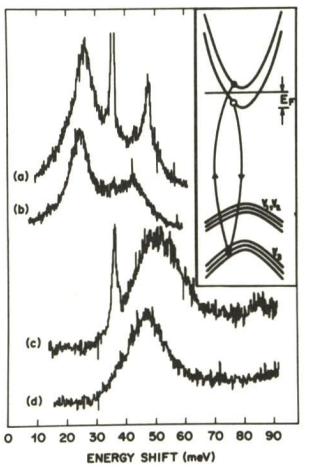

Fig. 5 Light-scattering spectra from two different samples (top and bottom): Wide bands result from electronic intersubband transitions. a)/c) and b)/d) represent different polarization of scattered light. Inset shows scattering process

[27,28]. Along with the density increase, we find a decrease in mobility (most prominent in the lower subband) which we relate to the increased density of ionized impurities in the walls and enhanced confinement of the lower state leading to increased scattering. The anticipated two-dimensional character of the system is most elegantly verified by angular-dependent SdH measurements. The angular dependence of the oscillations agrees excellently with the theoretical expectations for a 2DEG, see Fig. (4).

Measurements of oscillatory magnetoresistance limit our analysis to populated bound states. However, subband spacings in MD GaAs-(A&Ga)As superlattices were measured by inelastic light scattering [17,18]. To enhance the scattering cross-section, the experiments were performed with photon energies in resonance with the $E_o + \Delta_o$ energy gap of GaAs. The inset of Fig. (5) shows a schematic representation of the light scattering process. The spacing between subbands is directly reflected in the energy shift of the scattered light. Figure (5) shows energy shift spectra from two different samples. Several intersubband transitions were identified. The experimental results for the subband spacings are in good agreement with our model calculation of the subband structures[18] thereby indicating our general understanding of the MD-superlattice.

Being a useful tool to determine the subband level scheme, resonant inelastic light scattering has revealed other interesting properties of MD-superlattices. The most significant has been the first direct determination of the depolarization field effect (resonant screening) of intersubband excitations of a 2DEG. This was possible through the simultaneous observation of single particle and collective excitations [29].

From the preceding, we may conclude that nowadays a general understanding of the energy levels and the scattering mechanisms in MD-superlattices has been achieved. There is room for improvement and usage.

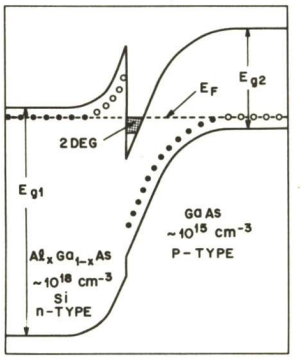

Fig. 6 Diagram of the band bending in a single MD GaAs-(AlGa)As interface

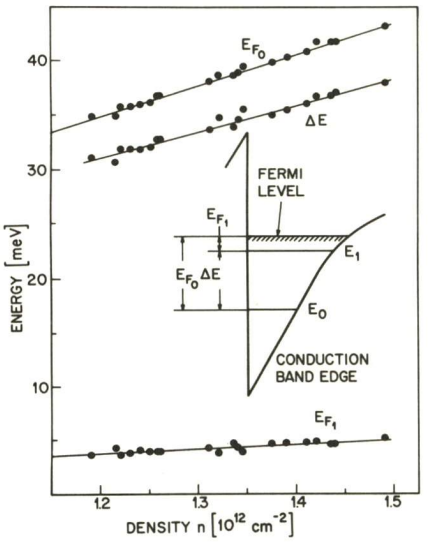

Fig. 7 Density dependence of subband splitting in a single MD GaAs-(AlGa)As interface

Single Interface

At first glance, the strong deformation of the initial square well potential in MD-superlattices is quite undesirable because it complicates matters considerably. However, this band bending can be utilized in an elegant way to create a 2DEG at a single heterojunction, the junction of two bulk semiconductors [11,12]. Examining the inset of Fig. (3) closely, one notices that the two lowest states ($E_{0/1}$, degenerate) are confined to one of the interfaces almost exclusively by means of the strong internal electric field. Removal of the opposite interface would hardly effect one of these bound states. This observation led to the design of a structure shown in Fig. (6). The physical realization is achieved in MBE by covering a several micron thick layer of undoped GaAs with a several micron thick layer of (AlGa)As doped with Si to a level of $\sim 10^{18}$ cm^{-3}.

Initial SdH-measurements proved the correctness of these ideas. Population of two separate levels bound by the quasi-triangular potential well at the interface were found in this sample. Again the angular dependence of the SdH-oscillations gives proof of the two-dimensionality of the electronic system under study. A strong persistent photoconductive effect is present as well and allows one to vary the carrier density continuously from 1.2 to 1.5×10^{12} cm^{-2} by pulsed illumination. The density dependence of the subband splitting ΔE of this structure is shown in Fig. (7). The expected increase of ΔE with increasing carrier density, i.e. increasing slope of the potential well, is found. Theoretical results on this interface structure [30] deviates from our data by approximately 15%. However, this discrepancy might largely be due to insufficient knowledge of some material parameters that enter the theoretical calculations. Hall measurements on single MD-interfaces reveal a temperature dependence of the mobility similar to that of MD-superlattices (see Fig. (2)). In agreement with the observation that single interface structures represent the ultimate limit of a very wide superlattice, one generally finds their mobilities to rank in the high-mobility range of MD-superlattices.

To illustrate the principal transport properties of single MD-interfaces further we show in Fig. (8) FIR transmission data in high magnetic fields of a sample with a low temperature Hall-mobility

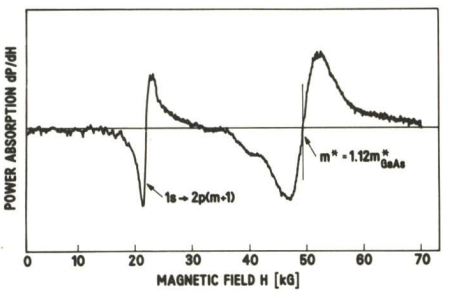

Fig. 8 Low temperature power absorption of 1840 GHz radiation by a single MD GaAs-(AlGa)As interface: Field normal to the layers

of 25 500 $cm^2/Vsec$ [11]. A bulk related donor transition and cyclotron resonance (CR) from the 2DEG are the prominent features. The width of the CR line agrees with the Hall-data. Its position reveals a mass increase of 12% of the confined carriers compared to the bulk GaAs band edge mass. Most of the increase must be attributed to the nonparabolicity of the conduction band of GaAs as a simple calculation shows and does not result from many particle effects like in Si-MOS structures. Lightscattering measurements, similar to those in MD-superlattices, have been performed successfully in single MD-interfaces as well [17].

The single MD-interface, though being in many ways similar to MD-superlattices, has two outstanding features. First, the 2DEG is confined to the interface between two bulk materials so that MBE is not absolutely necessary for its preparation as has been demonstrated recently with LPE-grown MD-interfaces [15]. Second, in a suitable arrangement the carrier concentration can be varied via an external gate voltage. These features make a single MD-interface extremely attractive for device considerations and first reports about successful implementation are available [14].

p-Type Structures

So far, we only dealt with the conduction band discontinuity of GaAs-(AlGa)As structures. However, considering the symmetry in the energy gap alignment between GaAs and (AlGa)As (see Fig. (1) and inset Fig. (9)) and the symmetry between electrons/donor-impurities and holes/acceptor-impurities in semiconductor physics, the existence of the counterpart of the 2DEG, the two-dimensional hole gas (2DHG), can be readily conceived. The energetic conditions resulting from step height, binding energy and carrier mass are less favorable than in the 2DEG case, but the requirements for two-dimensional confinement can be met by suitable choice of parameters [16].

Figure (9) shows Hall data on a MBE-grown GaAs-(AlGa)As:Be single MD-interface structure with individual layer thickness of $\sim$ 1.5 µm. The high value of the mobility and the saturation of the density at low temperatures are very similar to earlier results on n-type structures and suggest a similar mechanism to be present. Angular dependent SdH-measurements confirm this interpretation by showing once more the correct cos(θ)-behavior of the oscillation period as a function of field direction, an indication for the two-dimensionality of the system, Fig. (10). In accordance with the theoretical expectation of the sequence of levels in the triangular well, the temperature dependence of the oscillation amplitude yields an effective mass for the carriers of $0.35 \pm 0.1\ m_o$ which is only slightly smaller than the heavy hole mass of GaAs. The result on the single interface suggests that p-type MD-superlattices are practicable as well. Their existence has been verified experimentally and their properties have been found to be similar to those of n-type MD-superlattices [31].

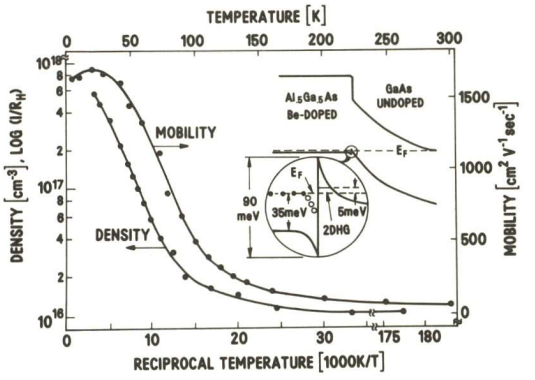

Fig. 9 Temperature dependence of Hall-density and Hall-mobility of single p-type MD-interface: Notice different scales

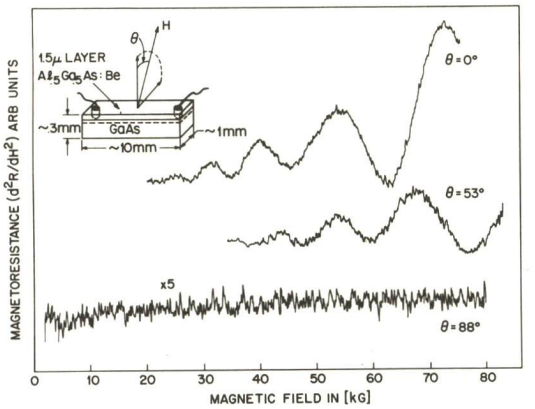

Fig. 10 Angular dependence of SdH-effect

Summary

We described a novel doping technique for semiconductor heterojunction superlattices and interfaces which spatially separates the mobile carriers from their parent impurities. This separation leads to strongly improved electronic transport properties along the layers of the material. The very high mobilities in the He-temperature range allowed for a variety of experimental investigations on these two-dimensional electronic systems which led to a general understanding of their properties. The superlattice-aspect of MD-structures has not yet been used to study transport perpendicular to the superlattice layers and interaction between neighboring layers. Investigation of this kind seem to be particularly interesting in alternating highly mobile 2DEG's and 2DHG's [6,32] both of which have now been demonstrated in the GaAs-(AlGa)As system.

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