Pressure studies of tunneling processes through a doped barrier

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We have investigated the influence of hydrostatic pressure on the tunneling processes between two independently contacted two-dimensional electron gas systems which are separated by a doped AlGaAs barrier. For magnetotunneling data, the pressure dependence of the GaAs effective mass m^* was determined between $p=0$ and 10 kbar. In this range, we find a linear pressure dependence of $d(m^*/m_e)/dp = 8\times10^{-4}\ \text{kbar}^{-1}$ for the electrons in the two-dimensional channels. At higher pressures several new resonances are observed, which correspond to transition energies in the order of 4 meV. These effects are most probably explained by local phonon modes related to the *DX* centers inside the barrier.

As it has been demonstrated recently,[1-4] hydrostatic pressure offers a very useful tool to study various aspects of electron tunneling in III-V semiconductor heterostructures. Applying pressure to such systems causes essential changes in the energetic positions of the conduction-band minima. Particularly, the Γ point of the Brillouin zone increases at a rate of 10.5 meV/kbar, whereas the X point is shifted down by 1.5 meV/kbar with respect to the top of the valence band.[5,6] Since the pressure coefficients of GaAs and AlGaAs are similar and the band offsets are weakly dependent on pressure, one can precisely predict and generate modifications of discontinuities in the potential profiles at the interfaces of the tunneling device. For GaAs-AlGaAs double barriers, it has been anticipated[7] that resonant tunneling processes are controlled by the Γ-Γ barrier, whereas nonresonant tunneling goes through the Γ-X barrier. An increase of the tunneling effective mass in $Al_xGa_{1-x}As$ barriers with increasing x confirmed the above conclusion.[8]

For instance, there are effects related to a so-called alloy splitting of the *DX* level due to a variation of the donor surrounding in the deformed lattice of $Al_xGa_{1-x}As$.[9,10] Experimental data on the microscopic parameters describing the lattice relation, such as a shift of atoms and local phonon modes, still remain scarce.[11] Properties of *DX* centers are highly pressure sensitive, and crystal lattice as well as electron band-structure contributions are important here.[12]

In this letter, we report about pressure studies on the samples, on which detailed tunneling experiments between barrier separated two-dimensional (2D) electron gas systems were performed previously.[13,14] Investigating magneto-tunneling processes between different Landau levels, the value of the GaAs effective mass m^* and its pressure dependence is determined directly. New resonances appearing at high pressure ($p>9$ kbar) suggest inelastic scattering processes due to local phonon modes related to the *DX* centers inside the doped barrier.

The samples consist of an unintentionally p-doped GaAs layer grown on a semi-insulating substrate ($N_A<1\times10^{14}\ \text{cm}^{-3}$), followed by an undoped spacer ($d=50$ Å), doped $Al_xGa_{1-x}As$ ($d=50$ Å, $n=4\times10^{18}\ \text{cm}^{-3}$, $x=35\%$), another spacer ($d=100$ Å), and n-doped GaAs ($d=800$ Å, $n=1.2\times10^{15}\ \text{cm}^{-3}$). An additional GaAs cap layer was highly n doped ($d=150$ Å, $n=6.2\times10^{18}\ \text{cm}^{-3}$). Shubnikov–de Haas measurements were used to determine the electron concentrations in the inversion and accumulation layer ($n^{\text{inv}}=6.3\times10^{11}\ \text{cm}^{-2}$, $n^{\text{acc}}=5.7\times10^{11}\ \text{cm}^{-2}$ at $p=0$ kbar). Ohmic contacts to both channels were aligned using a AuGe alloy. To establish the tunneling contact, AuGe was diffused slightly into the upper GaAs layers. Finally, the GaAs layer around the top contact was removed selectively, yielding independent contacts to both 2D channels. The resulting band structure of the used device is shown in Fig. 1(a). By applying a voltage V_b, the 2D states are shifted energetically with respect to each other. All transitions between these states are reflected in the tunneling current, allowing a direct determination of the 2D quantization energies and the energies of possible barrier states. The measurements of the current-voltage (I-V) characteristics and its derivative (dI/dV) were made using a four-terminal conductance bridge[15] at a modulation frequency of 22 Hz and a modulation voltage of 0.1 mV to achieve a high resolution. For high-pressure measurements the UNIPRESS clamp cell with light petroleum as a pressure transmitting medium has been employed. A calibrated highly Te-doped InSb pressure gauge was used to monitor the pressure at temperatures between $T=300$ and 4.2 K. Hydrostatic pressure was applied at room temperatures and the cell was subsequently cooled to $T=4.2$ K. Falls of pressure during cooling were in the range of $p=2$–3 kbar. Figure 1(b) schematically shows the changes in the band structure and the position of the *DX* level for a pressure of 10 kbar.

Figure 2 shows selected dI/dV_b curves of a typical sample traced at $T=4.2$ K for different pressures and different magnetic fields. In curve (1), the large peaks correspond to resonant tunneling processes between the lowest subband in the accumulation layer E_0^{acc} and the subbands in the inversion layer E_n^{inv} (0–n transitions). With increasing applied pressure, a higher and higher amount of electrons is trapped by the *DX* centers. A respective decrease in the densities in the 2DEGs as well as a lower number of

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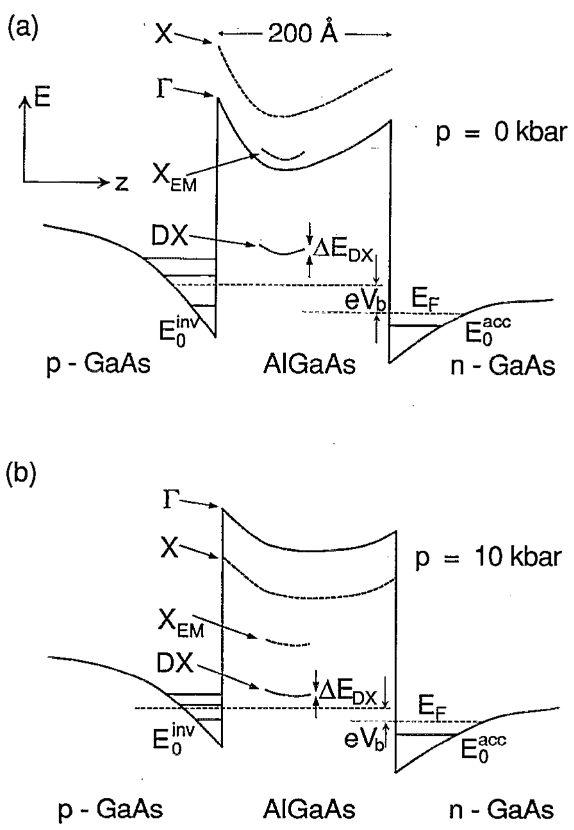

FIG. 1. Sample band structure for (a) $p=0$ kbar and (b) $p=10$ kbar. The band profile of the Γ valley is indicated by the solid lines; the X-valley profile of the AlGaAs barrier is indicated by a dashed line. X_{EM} is the effective-mass-like donor state belonging to the X valley. DX denote the DX-related levels. ΔE_{DX} is the band bending induced level broadening.

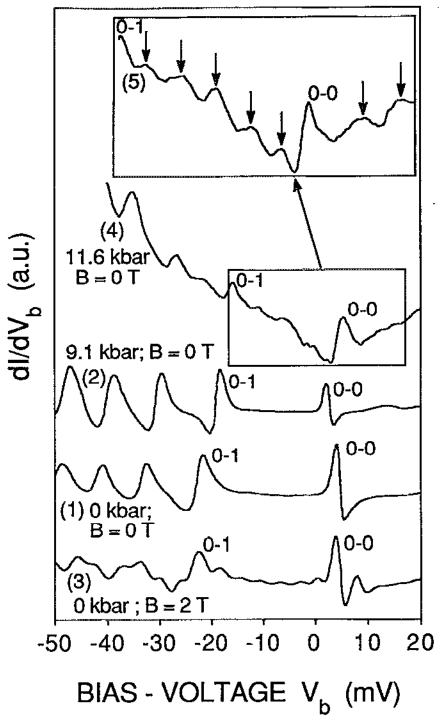

FIG. 2. Selected dI/dV_b curves vs bias voltage, measured at different pressures and magnetic fields. Curves 1–4 are traced at the same sensitivity but shifted to fit on the same plot. Curve 5 shows an enlarged cut of curve 4, recorded with higher resolution.

positive charges in the barrier results in a decreasing energetic separation of the subbands in the 2D channels. This effect is clearly observed in the dI/dV curves for pressures between $p=0$ and 9.1 kbar [curve (2)]. After magnetic fields are applied perpendicular to the sample, tunneling processes between different Landau levels on both sides of the barrier are evident as an additional a series of equidistant peaks [curve (3)]. These individual structures are observed up to about $B=5$ T and $p=10$ kbar.

At even higher pressure, the shape of the dI/dV_b curves is drastically changed. Although one can still identify the single intersubband resonances in curve (4), the strength of these resonances is strongly decreased while the background contribution of the conductivity is increased. At such high-pressure values the X point of the $Al_xGa_{1-x}As$ conduction band has already crossed the Γ point. Therefore, the lower X barrier might be responsible for the increased contribution of nonresonant tunneling electrons to the tunneling current. In addition, completely new structures are revealed between the (0-0) and the (0-1) transition, which are marked by arrows in curve (5). Their low amplitude and the small separation make it difficult to answer the question about their pressure dependence. For pressures as high as $p=13.5$ kbar all structures disappear due to the complete freeze out of all free carriers in the 2D channels.

As the peak positions of the Landau level-Landau level transitions are easily measured with a resolution better than 0.1 mV, the effective mass of the electrons in the two-dimensional channels can be determined with high accuracy in the interesting range of pressures, which brings the Γ-X barrier in the AlGaAs below the potential profile of the Γ-Γ barrier. After the energy of the incoming electrons is tuned by the applied voltage V_b, tunneling between different Landau levels on both sides of the barrier occurs each time, the relative energy shift of the Landau levels ΔE in both channels is equal $n\hbar\omega_c$ (Ref. 14). Self-consistent calculations have shown that the energy shift ΔE is approximately equal to $\Delta E=e\Delta V_b$.[16] Thus, the GaAs effective mass could be determined directly from the dI/dV_b peak positions via $\Delta E=\hbar\omega_c=\hbar eB/m^*$. to obtain a more precise value of $\hbar\omega_c$, however, the energy shift ΔE was calculated self-consistently as a function of the applied voltage V_b. The values of the effective mass obtained in this way are plotted in Fig. 3 as a function of the applied pressure. The zero pressure value of the effective mass ($m^*/m_e=0.066\pm0.001$) is in good agreement with the commonly accepted value. With increasing pressure, m^* changes at a rate of $d(m^*/m_e)/dp=(8\pm1)\times10^{-4}$ kbar^{-1}. This pressure coefficient for the GaAs effective mass is similar to the value determined from magnetophonon measurements in bulk GaAs,[17] where m^* increases by 0.74%/kbar. For heterostructures, a value of 1%/kbar was reported.[18]

For pressure between $p=10$ and 12 kbar, additional structures in the dI/dV_b characteristic are observed for

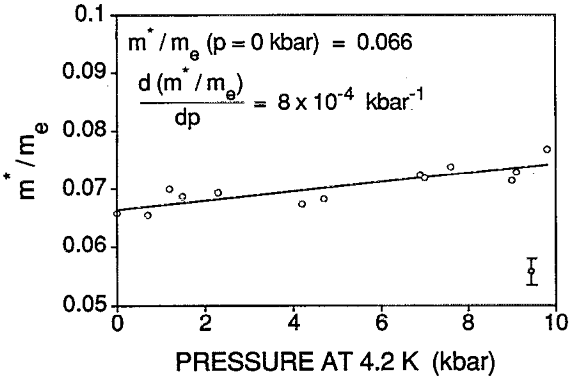

FIG. 3. Measured GaAs effective mass vs hydrostatic pressure.

negative as well as for positive bias voltages (Fig. 2, curves 4 and 5). Therefore, an involvement of the $Al_xGa_{1-x}As$ barrier in the tunneling process has to be taken into account.

Tunneling experiments were already used to investigate energy positions of deep states inside a barrier.[19,20] In our experiment, the high pressure energetically aligns the positions of the localized *DX* state and the quasibound states in the 2D channels. Thus, it is suggestive to consider for example tunneling of electrons through alloy splitted *DX* states,[9] where the four possible electronic levels of a *DX* center in $Al_xGa_{1-x}As$ could influence the electron transfer between the two 2D channels. According to most recent experiments,[10] the energetic separations of the considered states have been found to be in the range between 20 and 80 meV. This fact eliminates the alloy splitting effect being responsible for the new resonances observed in our experiment.

Also the effective-mass-like state belonging to the *X* valley of the AlGaAs barrier (X_{EM} in Fig. 1) is still above the *DX* center. This rules out that these states are involved in the observed effect.

Another suggestion is to associate this additional high-pressure feature in the tunneling characteristic with inelastic scattering of electrons by quasilocal phonon modes. These modes originate from lattice relaxation processes, accompanying the formation of the *DX* center.[11] Their energy is reported to be about 6 meV (Ref. 21) for zero applied pressure.

However, we are not able to observe these modes at pressure values below $p = 10$ kbar. To explain this behavior, the pressure dependence of the band bending has to be taken into account. At low pressure, the high density of electrons in the 2D channels and the high density of charges inside the barrier cause a large band bending in the potential profile. Therefore, the spatial energy dependence of the barrier states is relatively large. A rough estimation of the bandwidth of the *DX* related levels at $p = 0$ kbar gives a value of $\Delta E_{DX} = 10$ meV. The decreased charge concentration at high pressure leads to a drastic reduction of the band bending in our system. Thus, the estimated bandwidth of the *DX*-related level is less than 2 meV at $p > 10$ kbar, making it possible to resolve level spacings of this order.

In summary, we have investigated the influence of hydrostatic pressure on the tunneling processes between two 2D systems which are separated by a doped barrier. Using magnetotunneling experiments, the GaAs effective mass and its pressure dependence were directly determined from the transition energies between barrier separated Landau levels. As a result, we obtain a pressure coefficient of $d(m^*/m_e)/dp = 8 \times 10^{-4}\ \mathrm{kbar}^{-1}$, which is in good agreement with the values given in literature. New structures in the dI/dV_b characteristics are also observed above 10 kbar. From the corresponding energy of these transitions we propose that these structures are due to local phonon modes related to *DX* center in the barrier.

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