# Thermally activated intersubband and hopping transport in center-doped *p*-type GaAs/$Al_xGa_{1-x}As$ quantum wells

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We present variable temperature resistivity and magnetotransport data for GaAs/$Al_xGa_{1-x}As$ quantum wells, which are Be doped in the central part of the wells at doping concentrations ranging from moderate levels to well above the degenerate limit. We provide an investigation of possible transport mechanisms. For nondegenerate structures, the activation of free carriers with a measured activation energy of $E_{act}=29-36$ meV is close to the binding energy of the Be acceptor in $Al_{0.3}Ga_{0.7}As$/GaAs center-doped quantum wells. The dopant concentration corresponding to the transition from being nondegenerate to the degenerate limit is $<6\times10^{18}$ cm$^{-3}$. For degenerate conditions, the variable-range-hopping 2D transport with $\rho\sim\exp(T_0/T)^{1/3}$, Mott's law, which is observed at lower temperatures, occurs due to the strong localization of holes in the impurity potential fluctuations. For higher temperatures, the observed thermally activated transport is discussed in terms of the excitation of holes from the symmetric ground state into the antisymmetric excited states. The calculated intersubband energies according to a self-consistent solution of the coupled Poisson and Schrödinger equations are in good quantitative agreement with the experimental data.

## I. INTRODUCTION

Transport measurements provide essential information for fundamental studies of localization effects. The transport properties of modulation-doped quantum structures have been thoroughly investigated, due to their high mobilities. However, transport phenomena in center-doped quantum wells (CDQW's) have not received much attention. The probable reason is that the introduction of a small concentration of impurities into the region of the two-dimensional (2D) conductivity is known to degrade the mobility dramatically.[1] Information regarding physical phenomena can be obtained when $\delta$-doping layers are located inside a quantum well (QW), because of the extra degree of control provided by the heterojunction confinement.

The transport mechanisms in such structures are of fundamental interest, since transport phenomena in CDQW's are expected to be strongly affected by the confinement effects. A further advantage of such a nonuniform doping is that, by varying the width of the well or the dopant spike, it is possible to control the energy distribution of the carriers. Due to the different symmetry of the ground and exited states in the QW,[2] the energy distribution of majority carriers can affect the transport phenomena in a fundamental way, as it has been observed experimentally for *n*-type GaAs:Si CDQW's.[2] However, for *n*-type doping, the energy difference between the ground and the first excited subbands is of the order of 100 meV for a typical well thickness of 100–200 Å.[3] These values are much larger than the thermal energy $kT\sim26$ meV at 300 K. Thus, intersubband transition phenomena can only affect the transport properties under high electric fields, which cause the heating of conducting electrons.[2] The effect is accordingly expected to be negligibly small for the low-field equilibrium transport in 2D structures slightly above the degenerate limit.[4] For *p*-type 2D structures, on the other hand, the energy difference between subbands is approximately ten times lower, as compared with similar *n*-type quantum structures.[5,6] Thus, for *p*-type structures, the thermal activation of holes into the higher empty subband can be realized, even for moderately doped structures slightly above the degenerate limit under low electric fields. This process can affect the temperature behavior of the transport characteristics of *p*-type 2D systems.

In this paper, we report on detailed temperature dependent studies of the hole conductivity in *p*-type CDQW's. It is shown that the low-temperature hole transport in degenerate structures is governed by the hopping conductance in the variable-range-hopping (VRH) regime. For higher temperatures, the observed thermally activated conductivity is discussed in terms of the carrier activation into the next unoccupied subband.

## II. EXPERIMENT

The investigated GaAs/$Al_xGa_{1-x}As$ quantum structures were grown by molecular-beam epitaxy on semi-insulating (100) GaAs substrates, with a 0.35-$\mu$m buffer layer, including a smoothing superlattice. The growth temperature was nominally around 610 °C. Each structure contains 50 periods of (150 Å/150 Å) $Al_{0.3}Ga_{0.7}As$/GaAs. The central 30-Å region of each GaAs QW was uniformly doped with beryllium at concentrations ranging from $3\times10^{16}$ to $1\times10^{19}$ cm$^{-3}$. The measurements reported here were performed for a set of samples with five different doping levels of beryllium, as shown in the inset at Fig. 1.

The transport studies were performed within the temperature range 20–300 K in a superconductor solenoid magnet "Oxford SM 2000." Hall measurements were done under an

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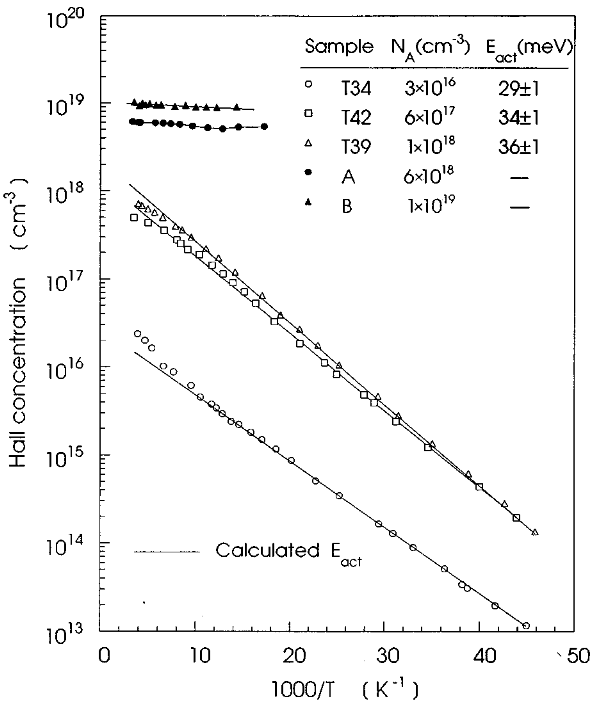


FIG. 1. The Hall concentration data for five OW samples, with acceptor doping in the range from $3\times10^{16}$ up to $1\times10^{19}$ cm$^{-3}$. The table yields essential information for each sample, such as the doping level and activation energy, as determined from the fit.

applied magnetic field of 0.5 T. All transport data presented in this paper were taken by a low-amplitude pulsed dc-current (1–7 $\mu$A) technique. The magnetoresistance (MR) was measured in the presence of a magnetic field up to 5 T, with a direction normal to the plane of the CDQW's. Measurements were made in the dark on lithographically defined Hall bars with six Au/Zn/Au Ohmic contacts.

### III. RESULTS AND DISCUSSION

The variable-temperature Hall-effect data obtained for the CDQW structures with different Be doping are shown in Fig. 1. As can be seen in Fig. 1, the dopant concentration corresponding to the transition from the nondegenerate to the degenerate limit is $<6\times10^{18}$ cm$^{-3}$. Below this concentration, a temperature increase from 20 up to ~200 K results in an activation of free carriers, with a measured activation energy of $E_{act}$=29–36 meV (table in the inset of Fig. 1). This activation energy is close to the binding energy of the Be acceptor in $Al_{0.3}Ga_{0.7}As$/GaAs CDQW's.[5] For degenerate samples, the carrier concentration is temperature independent in the 60–300 K temperature range.

The variable-temperature resistance data obtained for the CDQW structures are presented in Fig. 2. The results are quoted in terms of the total resistivity for each sample. It is clear from Fig. 2(a) that the temperature dependence of the resistivity $\rho$, for the samples demonstrating nondegenerate transport, can be described according to the exponential law $\rho=\rho_0 \exp(\varepsilon_{1/kT})$ within the temperature range 20–100 K. The so derived values of $\varepsilon_1$ are ~17–18 meV [see Fig. 2(a)], i.e., corresponding to $E_{act}/2$. This is expected, since the carrier concentration $p$ is proportional to $p\sim\exp(E_{act}/2kT)$ and the measured mobilities values are practically temperature independent.

In this paper, we will focus our attention on two specific experimental facts observed in the low-field transport measurements of nondegenerate CDQW's: (i) The increase of the activation energy $E_{act}$ with increasing doping level $N_A$, as evident from Fig. 1. (ii) The abrupt reduction of mobility observed for the low-doped structure $T34$, when the temperature increases from 22 to 35 K. The latter fact causes the deviation of the $\rho(T)$ dependence from the exponential behavior observed for the lowest temperatures [Fig. 2(a)]. The detailed investigation of these peculiarities is in progress and will be the subject of a later paper.

The variable temperature resistance data, obtained for the degenerate CDQW structures $A$ and $B$, are presented in Fig. 2(b). As shown in Fig. 2(b), the resistance of these samples is practically constant within the temperature range 140–300 K and indicates "degenerate conductivity." Unexpectedly, the resistivity strikingly increases at a further decrease of temperature and can be described by the following temperature dependence: $\rho=\rho^* \exp(\varepsilon/kT)$. This temperature dependence

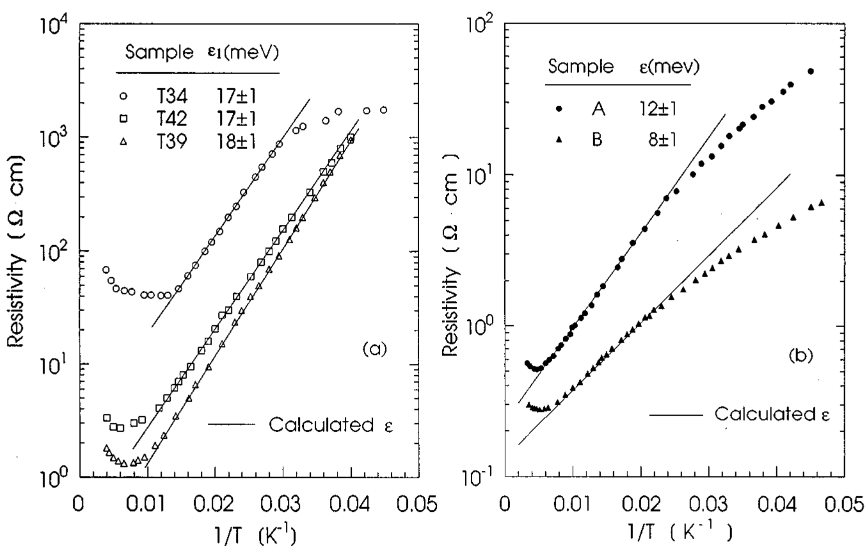


FIG. 2. The resistivity vs reciprocal temperature for (a) the nondegenerate samples, (b) the degenerate samples.

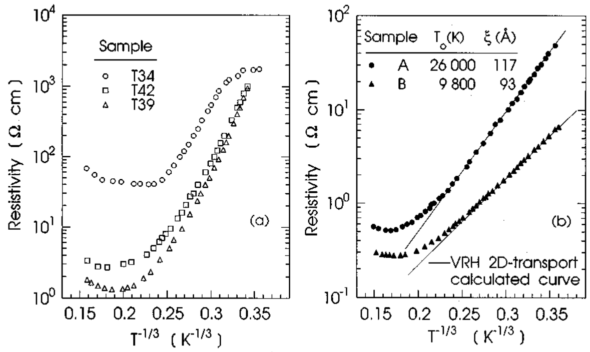


FIG. 3. The resistivity vs $T^{-1/3}$ (Mott's law for VRH-2D transport) for (a) the nondegenerate and (b) the degenerate samples, respectively.

observed in the degenerate structures indicates a thermal activation of the mobility. As evident from Fig. 2(b), this activation occurs within the temperature region $\sim 50 < T < 160$ K. The obtained values of $\varepsilon$ on the activation energies for samples *A* and *B* are $\varepsilon = 12 \pm 1$ and $8 \pm 1$ meV, respectively. For even lower temperatures, the characteristic temperature dependence $\rho \sim \exp(T_0/T)^{1/3}$, i.e., Mott's law for a noninteracting 2D-carrier gas in the VRH regime,[7] is observed. The resistivity of low-doped structures, on the other hand, *cannot* be described by a similar temperature dependence $\rho \sim \exp(T_0/T)^{1/3}$ within the entire temperature range, as is obvious from Fig. 3(a). This fact indicates the absence of hopping conductivity for nondegenerate structures.

The observation of such a temperature dependence of the conductivity in the degenerate system is quite remarkable. First of all, the 2D-hopping conduction is usually observed below the metal-insulator transition after the formation of the impurity band. At low temperatures, only the presence of residual donors for the *p*-type material can create vacant positions in the impurity band, because some small compensation has already taken place and gives rise to 2D-hopping conductivity in the QW plane. In the degenerate limit, the hole subbands are partly filled and the low-temperature conductivity is usually metal like.[8] The experimental observation of hopping transport provides evidence for a strong carrier localization. To estimate the localization length $\xi$ of the hole wave function, we have used the known Mott's equation, $kT = 3.5/[g(\epsilon_F)\xi^2]$, where $g(\epsilon_F)$ is the density of states at the Fermi level. The estimated values are as follows: $T_0 = 26\,000$, $\xi = 93$ Å for sample *A* and $T_0 = 9800$, $\xi = 117$ Å for sample B. The density of states $g(\epsilon_F)$ was assumed to be energy independent.[9] These estimated localization lengths are comparable with the interhole spacing (100 and $\sim 150$ Å for samples *A* and *B*, respectively) and indicate strong localization conditions.

It should be noted that the observed temperature range for VRH conductivity is not typical. High-temperature hopping has only been reported for low-doped *p*-type bulk GaAs grown at a low temperature,[10,11] which is attributed to strong fluctuations of the potential. Considering that the localization of the wave function of the symmetrical ground states for heavy holes (hh) and light holes (lh) coincides with the geometrical localization of the dopant spike, a strong influence of the impurity related potential fluctuations on the transport

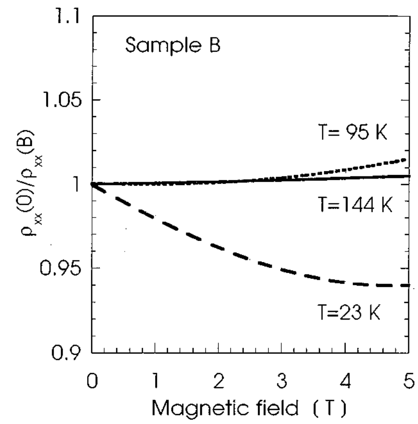


FIG. 4. Normalized magnetoresistance for three different temperatures $T = 23$, 95, and 144 K, for sample *B* ($N_A = 1 \times 10^{19}$ cm$^{-3}$).

parameters of the 2D hole gas (2DHG) is expected. Thus, we propose that the main mechanism of the observed low-temperature VRH transport is the strong localization of the 2DHG at the impurity related potential fluctuations. The presence of such potential fluctuations has also been demonstrated for *n*-type GaAs/$Al_xGa_{1-x}$As CDQW structures by photoluminescence spectroscopy.[12]

Figure 4 demonstrates the MR data for sample *A* at different temperatures. As can be seen in Fig. 4, a weak negative MR is observed only in the VRH regime, supporting the idea of transport under strong localization conditions.[13] As has been observed earlier,[14] the negative MR in the VRH regime under degenerate conditions for the 2D electron gas (2DEG) corresponds to the influence of the random potential fluctuations, due to impurities on the localization length. The MR data for sample *A* are similar to what is observed for sample *B*.

Let us now return to Fig. 2(b) and consider the thermal activation of the mobility in more detail. As mentioned before, the determined activation energy is approximately $\sim 10$ meV, which is much higher than the typical energies 1–3 meV usually observed for nearest-neighbor hopping (NNH) under impurity band conductivity conditions.[8] In order to clarify the activation mechanism involved in the investigated *p*-type CDQW's and taking into account that the measured activation energy is very close to the energy separation between the hole subbands,[5,6] we will consider the change of the subband structure of the GaAs QW, which the central doping gives rise to.

In order to quantitatively estimate the energy-level transformation with doping, we calculated the valence-band structure based on a self-consistent solution of the coupled Poisson and Schrödinger equations. The dopant atoms were assumed to be homogeneously distributed over the central 30 Å of the 150-Å-wide QW. Some important results of the numerical calculations for the subbands in a *p*-type GaAs/$Al_xGa_{1-x}$As CDQW are shown in Fig. 5. The measured value $\varepsilon$ for the thermal activation energy for the conductivity is in a good quantitative agreement with the calculated separation between the Fermi level, $\epsilon_F$, and the first excited antisymmetric hh subband $\epsilon_F - E_{hh2} = 11.5$ meV for sample *A* and 7.1 meV for sample *B*, respectively. We interpret the origin of the observed thermal activation of the con-

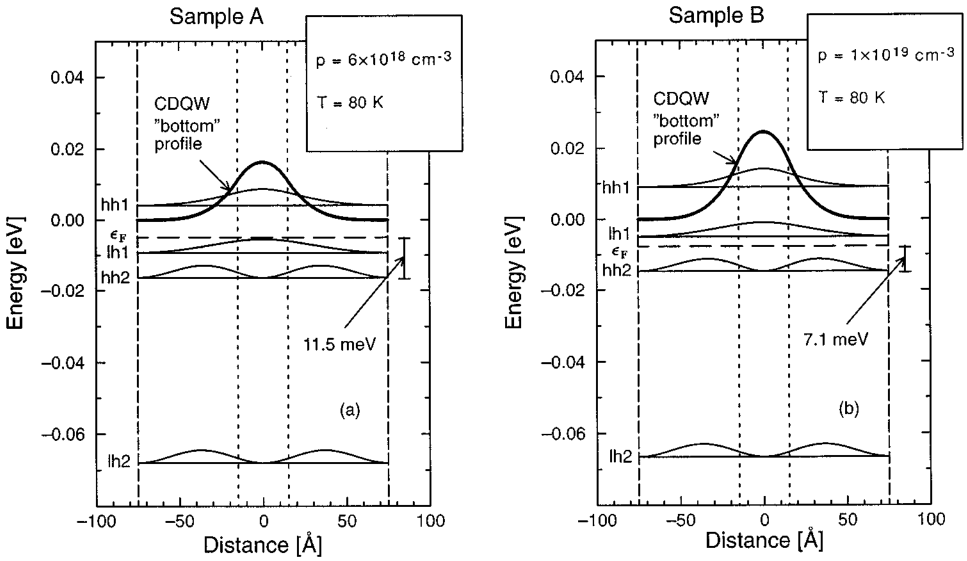


FIG. 5. Diagrams of the CDQW valence bands and the energies of the four subbands obtained from the self-consistent solution of the Poisson and Schrödinger equations, for the Be-doped GaAs/$Al_xGa_{1-x}As$ CDQW's with $p=6\times10^{18}$ $cm^{-3}$ (sample *A*) and $p=1\times10^{19}$ $cm^{-3}$ (sample *B*), respectively.

ductivity in terms of the model proposed by Masselink.[2] Accordingly, we suggest that the transport occurs due to the thermal excitation of holes from the ground state, which is symmetric and has a maximum overlap with the ionized acceptor spike, into an antisymmetric excited state, which has a minimum overlap with the impurities. Contrary to the $n$-type CDQW's structures, for which this transition is observed at high electric field conditions with hot electrons, this phenomenon dominates under low-field thermal equilibrium conditions, in our case, due to the small intersubband energy for the 2DHG (approximately ten times smaller than in the corresponding $n$-type CDQW's).

A possible alternative mechanism is the high-temperature NNH conductivity, due to the potential fluctuations.[10] However, we believe that this is not the major effect in our case. First of all, the MR data in the thermal activation conductivity range (Fig. 4) are typical for the classical low-field magnetotransport and do not support the localization mechanism, where the hopping transport dominates.[13] Second, the variable-temperature Hall-effect data in this conductivity range show a linear dependence of the Hall voltage with electric and magnetic fields. This is typical for the classical low-field free-carrier transport. On the contrary, in the VRH regime, we observe for both samples a nonlinear magnetic-field dependence of the Hall voltage at $B=0$–1 T, which is typical for hopping transport.[9,15] Thus the Hall measurements for degenerated samples are correct only within the high-temperature range (Fig. 1), where the nonlocalized transport is predominant.

In a limited temperature range, 40–65 K for sample *A*, and 35–50 K for sample *B*, corresponding to the transition from the strongly localized (VRH regime) to delocalized (activation) transport, the analysis is more difficult. As is obvious from Fig. 6, a fit for this narrow temperature range can be performed according to the $\rho\sim\exp(T^*/T)^{1/2}$ and $\rho\sim-\ln(T)$ dependencies. Both approximations are well known and are valid for the transport under localized conditions. The dependence, $\rho\sim\exp(T)^{-1/2}$, is known as the Efros-Shklovskii (ES) law and is usually observed in the VRH regime with Coulomb interaction between the hopping sites (so-called Coulomb gap).[13,16] However, the ES law is valid only at the *initial region* of the VRH regime with the *smooth transition to Mott's law under increasing temperature*.[17,18] In our experiments (see Fig. 6), the dependence with $\sim(1/T)^{1/2}$ slope is observed *after* Mott's slope $\sim(1/T)^{1/3}$ and, probably, cannot be explained by the peculiarities of localized transport. The $\rho\sim-\ln(T)$, which is typical for the weak localization,[19–21] is more realistic in our case. This temperature dependence for the resistivity has earlier been observed for 2D transport.[21–24] However, a proper analysis of the experimental data is unreliable, due to the small changes of $\rho$ within the limited temperature range 45–60 K.

## IV. CONCLUSIONS

We have both experimentally and theoretically studied the equilibrium transport related to holes in GaAs/$Al_xGa_{1-x}As$ quantum wells, which are Be doped in the central part of the wells at doping concentrations ranging from moderate levels to levels well above the degenerate limit. In the low-

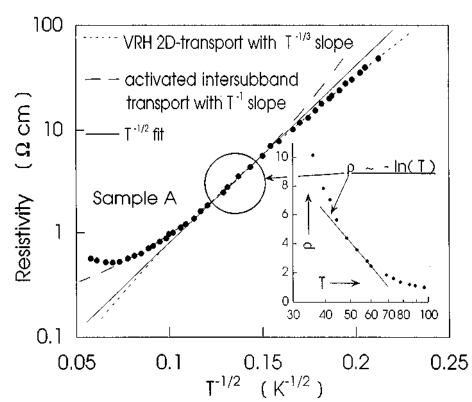


FIG. 6. The resistivity vs the $T^{-1/2}$ for sample *A* ($p=6\times10^{18}$ $cm^{-3}$). The logarithmic fit for the resistivity data in the inset corresponds to the data inside the circle in the main figure.

temperature range under degenerate conditions, the observed VRH-2D transport is explained in terms of strong 2DHG localization, due to potential fluctuations in the QW caused by the central doping. The experimentally observed negative MR and the estimated values of the localization lengths are in agreement with the proposed model. The thermal equilibrium phonon-assisted activation transport observed for degenerate structures is discussed in terms of hole transitions from the symmetric ground state into the antisymmetric excited states. The calculated intersubband energies are in a good quantitative agreement with those deduced from the experimental data.

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