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Solid State Communications xx (0000) 1–4

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Photoluminescence and transport in selectively doped p-GaAs/AlGaAs quantum wells: manifestation of the upper Hubbard band

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Received 23 December 2002; received in revised form 12 March 2003; accepted 12 March 2003 by E.L. Ivchenko

Abstract

By selective doping (Be) of the well and barrier regions of GaAs/Al_{0.3}Ga_{0.7}As structures we have realized the situation where the upper Hubbard band (A^+ centers) has been occupied by holes in the equilibrium. We studied the temperature behavior of the Hall effect, variable range hopping (VRH) conductivity and the photoluminescence (PL) spectra of the corresponding structures. The experimental data demonstrated that the binding energy of the A^+ states significantly increases with respect to 3D case and strongly depends on the well width (9 nm, 15 nm). The localization radii of the A^+ states estimated from the transport data are of the order of the well widths.

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PACS: 71.23.A; 78.20. – e; 73.90. + f

Keywords: D. Electronic states (localized); D. Electronic transport; A. Nanostructures

1. Introduction

A significant interest was restored recently to the investigations of transport in 2D structures. It was mainly related to the observation of a transition from the dielectric behavior of the conductance to the metallic one [1]. Since the metal–insulator transition in 2D contradicts with the scaling theory of localization, such a behavior was a puzzling one. Recently we made an attempt to explain the experimental results suggesting that the transport in corresponding structures being significantly affected by the localized states of the band tail including in the particular states of the upper Hubbard band [2]. However, an absence of independent information concerning the localized disorder-induced states in question prevents a direct comparison of the theoretical model and experimental

data. Correspondingly, the studies of transport over the upper Hubbard band in a model system with localized states of a known nature is of undoubted interest. Note that an observation of the upper Hubbard states in 3D is a difficult task since the theoretical estimates of the binding energies for the doubly occupied states are too small. Nevertheless our previous studies unambiguously exhibited a contribution of the upper Hubbard band to hopping magnetoresistance of different highly doped semiconductors. The corresponding experimental estimates of the Hubbard energy appeared to be much less than the theoretical estimates [3]. This fact can be in particular explained by a vicinity to the metal–insulator transition. Indeed, in this case the Hubbard energy $U = e^2/\kappa a$ decreased due to a divergence of both the localization radius a —and the dielectric constant— κ . Another factor emphasizing a role of the double occupied states is the 2D geometry. Indeed, in the narrow wells (where the spatial size of the site wave function is comparable to the well width) the binding energies of $D^-(A^+)$ states significantly increase which corresponds to a decrease of the Hubbard energy. These

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113 factors favor an observation of the corresponding contri-
 114 bution, the D^- singlet optical transition has been observed
 115 for Si doped multiple-quantum-well GaAs/Al_{0.3}Ga_{0.7}As
 116 structures [4]. Then, we would like to note that additional
 117 advantage is related to selectively doped structures where
 118 one can vary a relation between the numbers of single- and
 119 doubly occupied states. As shown by Larsen [5] in the case
 120 of equal doping concentrations in the center barrier and well
 121 regions, more than 60% of the well donors are converted
 122 into D^- states. If all donors are converted, an important
 123 consequence of this is that one cannot observe neutral
 124 donors at low temperatures but rather $D^-(A^+)$ states.

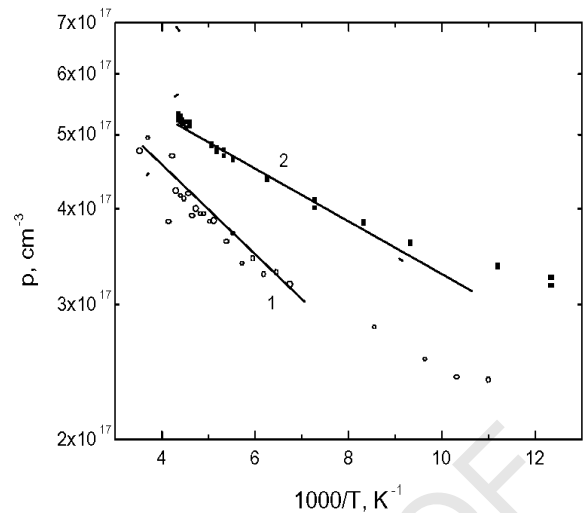
125 We have chosen systems GaAs/Al_{0.3}Ga_{0.7}As with the
 126 well width (d) equal to 15 and 9 nm, respectively, and some
 127 larger barrier width 25 nm, which were doped by an
 128 acceptor dopant, Be (with a localization length = 2 nm
 129 being much less than d). By a selective doping of the central
 130 regions with relative widths 1/3 of both wells and barriers
 131 (with equal doping concentrations) we realized a situation
 132 where the upper Hubbard band was partly occupied in the
 133 equilibrium and the conductivity was controlled by the A^+
 134 states. We studied temperature behavior of the Hall effect,
 135 and of the variable range hopping (VRH) conductivity as
 136 well as the photoluminescence (PL) spectra of the
 137 corresponding structures. The experimental data demon-
 138 strated that the binding energy of the A^+ states significantly
 139 increases with respect to 3D case and strongly depends on
 140 the well width.

142 2. Experiment

143 The investigated GaAs/Al_{0.3}Ga_{0.7}As quantum well
 144 structures were grown by molecular-beam epitaxy on
 145 semi-insulating GaAs substrates with a buffer layer. Each
 146 structure contains 20 periods of 15 nm/25 nm GaAs/Al_{0.3}-
 147 Ga_{0.7}As or 9 nm/25 nm GaAs/Al_{0.3}Ga_{0.7}As. The central
 148 regions (with relative widths 1/3) of barriers and/or wells
 149 were uniformly doped with beryllium with concentration
 150 $5 \times 10^{17} \text{ cm}^{-3}$. The transport studies were performed within
 151 temperature interval 0.4–300 K for low dc current (10–
 152 100 nA). For the PL measurements we have used He–Ne
 153 laser, cooled photomultiplier, grating monochromator and
 154 fiber optics.

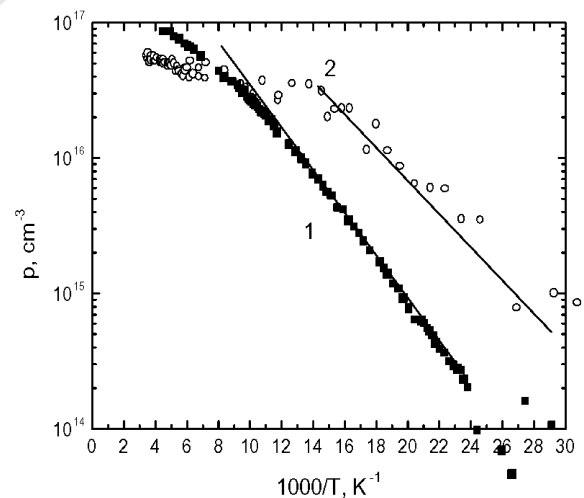
155 3. Results

156 The temperature behavior of the Hall concentration
 157 obtained for the selectively doped structures (wells and
 158 barriers) with A^+ centers is shown in Fig. 1. The activation
 159 energies extracted from the corresponding slopes are equal
 160 to 7 and 11 meV, for the well widths 15 nm (curve 2) and
 161 9 nm (curve 1), respectively. On the basis of the fact that the
 162 values of mobility in the temperature region 100–300 K are



169 Fig. 1. Temperature dependencies of carrier concentration for two
 170 samples (barrier and well regions are doped), 1—well width 9 nm,
 171 2—well width 15 nm.

172 large ($\mu = 10^3 \text{ cm}^2/\text{V s}$) we conclude that the activation
 173 energies correspond to ionization of the A^+ centers to the
 174 valence band. Note that the ionization energy of the A^+
 175 centers increases by a factor of 1.6 as a result of the well
 176 width decrease from 15 to 9 nm. For the comparison, in the
 177 Fig. 2 we have shown the Hall concentration data obtained
 178 for the selectively doped structures, where only well regions
 179 were doped and, correspondingly, the well acceptors formed
 180 A^0 centers. The obtained activation energies are 30 and
 181 23 meV for wells 9 nm (curve 1) and 15 nm (curve 2),
 182 respectively. They are close to the binding energy of the
 183 isolated A^0 (Be) acceptor in quantum well ($E_0 = 32 \text{ meV}$
 184 and $E_0 = 29 \text{ meV}$). The difference between the activation



185 Fig. 2. Temperature dependencies of carrier concentration for two
 186 samples (only well regions are doped), 1—well width 9 nm, 2—
 187 well width 15 nm.

energies and the binding energies mentioned above can be attributed to the finite energy width of the impurity band for this doping level. As one can see from Fig. 1 at low temperatures ($T < 100$ K) temperature dependence of Hall concentration trends to form a plateau which corresponds to a crossover to the hopping conductivity. The variable temperature resistance data for structures with A^+ centers are shown in Fig. 3. To describe the hopping transport for the samples with relatively slow temperature dependencies of the resistance one should take into account the preexponential factor. For the 2D hopping transport the expression for VRH conductivity accounting for temperature dependence of preexponential factor has a form [6]:

$$\sigma = \sigma_0 T^{-1} \exp\left(-\frac{T_0}{T}\right)^{1/3} \quad (1)$$

Here T_0 is the parameter related to the density of states at the Fermi level ($N(\varepsilon_F)$) and localization radius a :

$$T_0 = C(N(\varepsilon_F)a^2)^{-1} \quad (2)$$

$C = 13.8$ being a numerical coefficient. The values of T_0 are 5×10^3 and 3×10^3 K for the well widths 9 and 15 nm, respectively. If one assumes that the values of $N(\varepsilon_F)$ for these two cases are equal, one obtains for the localization radii ratio

$$\frac{a_1}{a_2} \sim \sqrt{\frac{T_{0,1}}{T_{0,2}}} \sim 1.3$$

From the positive magnetoresistance data we have evaluated the localization radius for sample with $d = 15$ as 11 nm [7], so the localization radius for the well with $d = 9$ nm is expected to be about 1.3 times smaller—8.5 nm. One can see that the localization radii are of the order of the well widths.

Fig. 4 shows typical PL spectra at $T = 4.2$ K for the

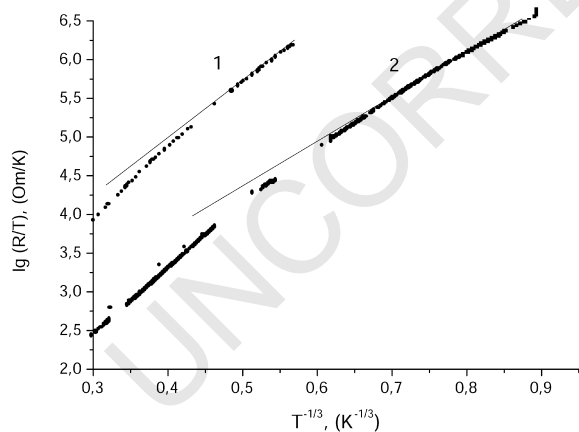


Fig. 3. Temperature dependencies of VRH conductivity for two samples (barrier and well regions are doped), 1—well width 9 nm, 2—well width 15 nm.

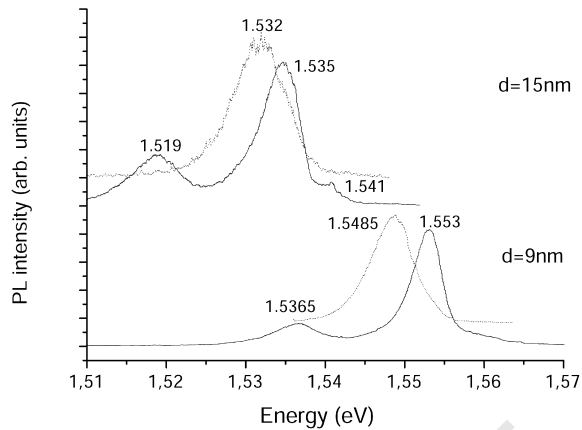


Fig. 4. Photoluminescence spectra at $T = 4.2$ K for the wells with $d = 15$ nm and $d = 9$ nm. Solid curves: only well regions doped; dotted curves: barrier and well regions doped.

wells with $d = 15$ and 9 nm. Solid curve corresponds to the PL spectrum of the structures containing A^0 centers. The spectrum consists of 3 lines. Its position agrees with existing data for the quantum wells with $d = 15$ nm and the same concentration of acceptors [8]. The line at 1.541 eV corresponds to a free hh-exciton, while the binding energy is $E_x = 7$ meV. The line at 1.535 eV can be attributed to the acceptor bound exciton with the binding energy $E_b = 4$ meV. The line at 1.519 eV is related to free to bound radiate recombination (electrons recombine to A^0 impurity). The position of this line allows to evaluate the impurity binding energy $E_0 = 27$ meV basing on the values of free exciton binding energy and bound exciton binding energy. The corresponding estimate agrees with known values of the binding energy for Be. The dot curve represents the PL spectrum of the structures containing A^+ centers. The characteristic feature of this spectrum is an absence of the standard exciton and impurity lines. The main peak at 1.532 eV is shifted by 3 meV with respect to the bound exciton peak. If we assume that this line is due to recombination of free electron with a hole bound on A^+ center, we can estimate the binding energy of the A^+ center as $E_{A^+} = 14$ meV on the base of the binding energies of the free exciton (E_x) and of the bound exciton (E_b).

A typical PL spectrum for the wells with $d = 9$ nm is shown in Fig. 4. The line at 1.553 eV can be attributed to the bound exciton with the binding energy 4 meV. The line at 1.5365 eV is related to free to bound radiate recombination (electrons recombine to A^0 impurity). The position of this line allows to evaluate the impurity binding energy 30 meV basing on the values of ($E_x = 9$ meV) and ($E_b = 4$ meV) for $d = 9$ nm. The corresponding estimate agrees with known values of the Be binding energy for this well width. The dot curve is related to structures containing A^+ centers and has one peak 1.5485 eV shifted with respect to the bound

exciton peak (in structures with A^0 centers) by 4.5 meV. On the base of the binding energies of the free exciton and of the bound exciton one estimates the binding energy of the A^+ center as 18 meV.

4. Discussion

First, we should address to the nature of the states observed in transport and PL data. There are two possible interpretations. These states can be ascribed, first, to the ground states of A^+ centers, or, second, to the states of ‘barrier acceptors’ (that is holes within the well being localized near the impurity ion within the barrier). There are some arguments against the second assumption. First in the modulation doped GaAs/Al_{0.3}Ga_{0.7}As quantum structures where only barrier were doped we have not observed any new PL lines which could be related to the new impurity states. Then, PL lines position in our experiments depends on the well width, but is not sensitive to the barrier width (20–35 nm). So we conclude that the states observed are indeed the ground states of A^+ centers. From both PL and transport data we found that the binding energy of the A^+ center is enhanced by a factor 1, 5 for the wells with $d = 9$ nm with respect to the well with $d = 15$ nm. Localization radius of the states in wells with $d = 9$ nm are evaluated to be about 1.3 times smaller than for the wells with $d = 15$ nm. Their values are comparable to the well widths.

However, the magnitudes of the binding energies of A^+ centers obtained from Hall data ($E_{A^+} = 7$ meV for $d = 15$ nm and $E_{A^+} = 11$ meV for $d = 9$ nm) are much smaller than the values obtained from PL ($E_{A^+} = 14$ meV for $d = 15$ nm and $E_{A^+} = 18$ meV for $d = 9$ nm) which is in contrast to the situation for the samples with A^0 centers. This fact can be explained as follows. The samples with A^0 centers do not exhibit a significant disorder potentials because practically all the centers are neutral. As a result, the binding energies estimated from the optical and Hall data are close to each other and are close to existing estimates for corresponding well widths given in literature [8]. On the other hand, when both the wells and the barriers are doped we deal with negative charges in the barriers and positive charges in the wells. Thus non-equilibrium electrons are first captured by the disorder potential and only then recombines with a hole localized on an acceptor—like in the case of donor–acceptor recombination. As a result, the observed photon energy appears to be less than energy related to free to bound radiate recombination by the scale of this potential. The disorder potential has a significant magnitude which may be rough estimated as $W \sim (e^2/\kappa)N_s^{1/2}$ where $N_s \sim 2N_a d/3$ is the 2D concentration of the charged defects (N_a is Be concentration); it gives an estimate $W \sim 10$ meV. The actual values of the binding energies are lower than the ones obtained from the optical data by the quantity W , and are in

a rough agreement with the Hall data. Due to this reason we consider the Hall data as more reliable.

As for the magnitudes of the binding energies of A^+ centers and the fact of its strong increase with a decrease of d (from $0.29E_0$ to $0.34E_0$ for $d = 15$ and 9 nm well widths), the corresponding features are unusual and need a further understanding. We compared it to the standard calculations performed for D^- centers [9] (no detailed calculations for A^+ centers are still available). However, the dependencies following from these calculations are not as sharp as the ones corresponding to our data. We believe that the behavior in question can be explained with an account of the polaron effect [10] as well as of the vicinity of the metal–insulator transition. One should have in mind that the critical concentration for the metal–insulator transition at the upper Hubbard band can be significantly smaller than for the lower one because of much larger localization length for the A^+ centers.

Summarizing, for the first time we have studied both transport and PL in the structures where the upper Hubbard band (A^+ centers) is occupied in the equilibrium. A special attention has been paid to the dependence of the parameters of the band (binding energies and radii) on the well width.

Acknowledgements

We are indebted to A.E. Zhukov, D.V. Shamshur, A.B. Chernyaev and D.N. Poloskin for their help in the growth of the QW-structures and measurements. We are also grateful to V.I. Kozub for helpful discussions and reading the manuscript. This work was financially supported by the Russian Foundation for Basic Research (project No. 00-020-16992 and No. 01-02-17912).

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