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A scientific session of the Division of General Physics and Astronomy of the Russian Academy of Sciences (RAS) was held on May 30, 2001 at the P N Lebedev Physics Institute, RAS. The following reports were presented at the session:

(1) **Vdovin E E, Khanin Yu N, Dubrovskiĭ Yu V** (Institute of Microelectronics Technology and High-Purity Materials, RAS, Moscow region, Chernogolovka), **Veretennikov A** (Institute of Solid-State Physics, RAS, Moscow region, Chernogolovka), **Levin A, Patane A, Eaves L, Main P C, Henini M** (The School of Physics and Astronomy, University of Nottingham, Nottingham, UK), **Hill G** (Department of Electronic and Electrical Engineering, University of Sheffield, Sheffield, UK) "Magnetotunneling spectroscopy imaging of electron wave functions in self-assembled InAs quantum dots";

(2) **Volkov V A, Takhtamirov É** (Institute of Radio Engineering and Electronics, RAS, Moscow), **Ivanov D Yu, Dubrovskiĭ Yu V** (Institute of Microelectronics Technology and High-Purity Materials, RAS, Moscow region, Chernogolovka), **Eaves L, Main P C, Henini M** (The School of Physics and Astronomy, University of Nottingham, Nottingham, UK), **Maude D K** (Grenoble High Magnetic Field Laboratory, MPI-CNRS, France), **Portal J-C** (Grenoble High Magnetic Field Laboratory, MPI-CNRS, Institut Universitaire de France, and Institut National des Sciences Appliquées, Toulouse, France), **Maan J C** (High Field Magnet Laboratory, Research Institute for Materials, University of Nijmegen, The Netherlands), **Hill G** (Department of Electronic and Electrical Engineering, University of Sheffield, Sheffield, UK) "Tunneling spectroscopy of quasi-two-dimensional plasmons";

(3) **Dvurechenskiĭ A V, Yakimov A I** (Institute of Semiconductor Physics, Siberian Branch of the Russian Academy of Sciences, Novosibirsk) "Quantum dot Ge/Si heterostructures";

(4) **Lozovik Yu E** (Institute of Spectroscopy, RAS, Moscow region, Troitsk) "Exciton Bose condensate control and the phonon laser";

(5) **Subashiev A V** (State Technical University, St.-Petersburg) "Effective polarized electron emitters based on semiconductor nanostructures".

An abridged version of these reports is given below.

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Magnetotunneling spectroscopy imaging of electron wave functions in self-assembled InAs quantum dots

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Quantum dots (QD) make up nanostructures in which electron motion is restricted in the three spatial directions. This leads to a series of discrete energy levels for the electrons in quantum dots, similar to the case of an atomic spectrum. In the last few years the energy spectra of the quantum dots that form in the process of growing strained epitaxial InAs layers by the Stranski – Krastanov method have been studied in various ways [1], but so far no experimental studies of the spatial distribution of the electron wave functions in InAs quantum dots have been conducted. Although scanning tunnel spectroscopy makes it possible to obtain an image of the electron distribution at (or near) the surface of a heterostructure [2], quantum dots are often located far from the surface. In the report we show how magnetotunneling spectroscopy can be used as a nondestructive method that makes it possible to experimentally extract information about the probability density distribution of the electron wave function in self-assembled quantum dots (SAQD) [3].

The samples used in the experiments were AlGaAs/GaAs double-barrier heterostructures with a thin InAs film at the center of the GaAs quantum well [1.8 and 2.3 monolayers (ML)]. The InAs self-assembled quantum dots form in the process of growing strained epitaxial InAs layers by the Stranski – Krastanov method. Substrates with surface orientations (311)B and (100) were used in growing the heterostructure by the molecular beam epitaxy (MBE) method. The differences in growth conditions for the strained InAs layers and in the substrate orientations led to differences in shape and size of the emerging quantum dots and hence to differences in their energy spectra. In addition, reference structures without InAs layers were used. Selective *n*-doping made it possible to create junctions from above and from the substrate side. The standard technology of chemical etching was employed to create a mesoscopic structure 20 – 100 μm in diameter (Fig. 1a).

The photoluminescence spectra of the samples grown on the substrates with (100) and (311) orientations and thicknesses of the InAs layers amounting to 1.8 and 2.3 ML as well as of samples grown on substrates with the (100) orientation

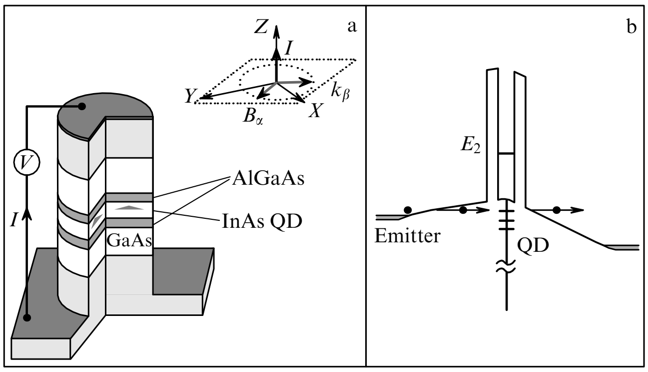

Figure 1. (a) Schematic of AlGaAs/GaAs resonance tunnel diode with a InAs self-assembled quantum dot at the center of a GaAs quantum well. Inset: mutual orientation of the magnetic field B and current I. X and Y are the principal crystallographic axes, α and β specify, respectively, the direction of B and of the electron momentum acquired, due to the Lorentz force, during tunneling. The pyramids depict the orientation of the quantum dot with respect to the coordinate axes. (b) Profile of the bottom of the conduction band.

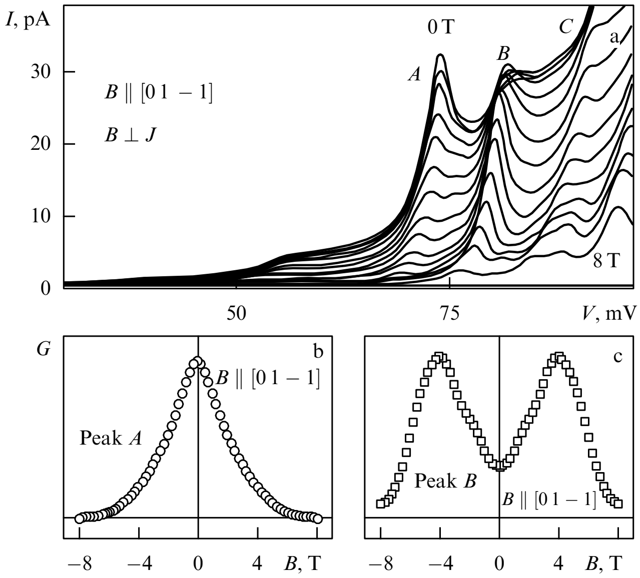

Figure 2. (a) Low-temperature ($T = 4.2$ K) current – voltage characteristics $I(V)$ in the presence of a magnetic field. The magnetic field strength changes from 0 to 8 T with a 0.5-T increment. The magnetic field B is perpendicular to the electric current. (b) and (c) The magnetic field dependence of the differential conductance, $G(B) = \mathrm{d}I/\mathrm{d}V$, with the magnetic field parallel to the [01 − 1] axis for different states of the quantum dots.

and the thickness of the InAs layer amounting to 1.8 ML exhibited a line with an energy of 1.27 – 1.35 eV, corresponding to the photoluminescence of InAs quantum dots. The characteristic size of the quantum dots ($\sim$ 20 nm) and the dot number density (0.5×10^{11} cm^{-2}) were determined by the scanning tunnel spectroscopy for samples grown in the same conditions as those under investigation. Transverse transmission electron microscopy (TTEM) was used directly to study a sample grown for tunnel transport measurements. The height of the dot was found to be about 2 – 3 nm.

The bottom profile of the conduction band of our heterostructure is depicted in Fig. 1b. The InAs layer of self-assembled quantum dots forms a set of electron states below the bottom of the conduction band in the GaAs quantum well. Some of these states are filled by electrons even under a zero bias, and in the region adjacent to the AlAs barriers these form a depleted layer. When a bias voltage is applied, tunneling through the discrete electron states leads to peaks in the current – voltage characteristics $I(V)$. These characteristics were measured by the standard direct-current method with a noise current less than 50 fA. The measurements were carried out in the 4.2 – 100-mK temperature range in magnetic fields of the induction up to 12 T.

We studied tunneling through InAs quantum dots in a magnetic field directed lengthwise of the growth plane (X, Y), i.e. perpendicular to the current. Below we shall consider samples grown on a (311)B substrate. In this plane, the principal crystallographic axes are [01−1] and [−233]. The results obtained for samples grown onto a (100) substrate are similar.

Figure 2a depicts the low-temperature ($T = 4.2$ K) current – voltage characteristics $I(V)$ in the presence of a magnetic field B. This magnetic field lies in the (X, Y) plane and is perpendicular to the electric current (see the inset to Fig. 1a). The [01−1] and [−233] axes determine the two principal crystallographic axes in the plane perpendicular to the direction of growth, [311]. The amplitude of each resonance strongly depends on the magnetic field strength. In particular, as B increases, the amplitude of the peak A decreases, while the amplitudes of the peaks B and C exhibit a nonmonotonic dependence on the magnetic field strength. Figures 2b and c clearly show two characteristic types of the magnetic-field dependence. Notice that all the resonances are suppressed in high magnetic fields.

But if at a certain fixed magnetic field strength the orientation of the magnetic field with respect to the principal crystallographic axes in the (X, Y) plane is varied, the amplitudes of the peaks begin to exhibit a strong dependence on this orientation (Fig. 3a), and the minima and maxima in the angular dependences of amplitudes of all the observed resonances for samples grown onto (311) substrates coincide, to within $\sim 15°$, with the principal crystallographic axes in this plane (Fig. 3b).

We can explain the magnetic-field dependence of the resonance amplitudes through examining the effect of the magnetic field on the tunneling electron. Let α, β, and z denote, respectively, the direction of B, the direction perpendicular to B in the growth plane (X, Y), and the direction perpendicular to the (X, Y) plane. When an electron tunnels from the emitter into the quantum dot in a magnetic field, it acquires an additional momentum $\Delta k_\beta = eB\Delta S/\hbar$, where ΔS is the effective tunneling length along z [4] (the momentum in the direction β changes due to the Lorentz force acting on the tunneling electron).

Applying a bias voltage to the heterostructure makes it possible to lower the energy of states of the quantum dots with respect to the emitter's Fermi energy and to observe peaks (when the energies coincide) in the current, corresponding to tunneling through these states at the quantum dot. Then, measuring the variation of the tunnel current caused by the variation of B, we can determine the value of the matrix element that describes the electron's transition from the emitter to the quantum dot. In our experiment we found it convenient to express the matrix element of the tunnel transition in terms of the Fourier transforms of the electron wave functions $\Phi_{i(f)}(k)$, where i and f correspond to the initial

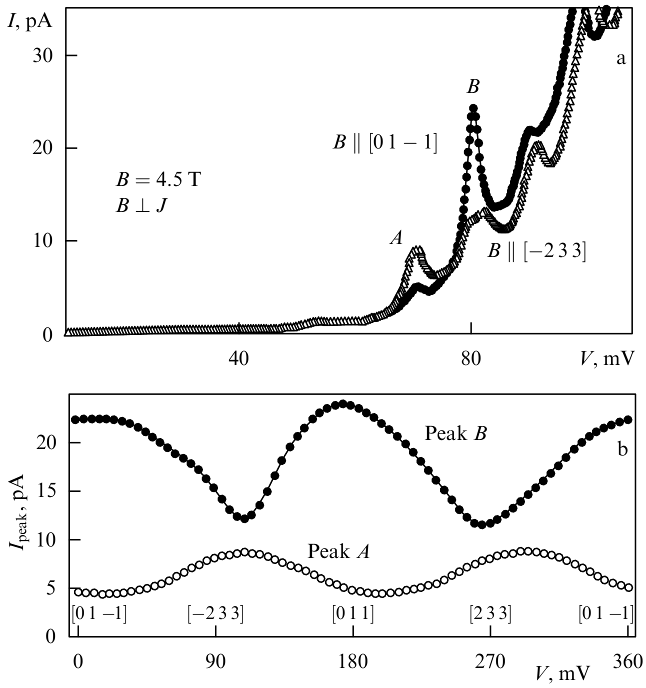

Figure 3. (a) Current–voltage characteristics $I(V)$ for the case of a magnetic field $B = 4.5$ T that is perpendicular to the electric current. The first curve (small black disks) represents the case where $B||[-1-1]$, and the second curve (small open triangles) represents the case where $B||[-233]$. (b) Angular dependence of the peak currents for the resonances A and B.

(emitter) and final (quantum dot) states between which the tunnel transition occurs [5, 6]. Note that the initial states of the emitter are rather weakly localized in the real space, in contrast to the strongly localized states of quantum dots. Hence $\Phi_i(k)$ in the k-space is represented by a Dirac delta function, which is nonzero only in the vicinity of $k = 0$. And since the tunnel current is determined by the square of the matrix element which contains both $\Phi_i(k)$ and $\Phi_f(k)$, the fact that $\Phi_i(k)$ is a Dirac delta function makes it possible to determine the shape of the function

$$\Phi_f(k) = \Phi_{\mathrm{QD}}(k)\,,$$

by varying B and hence k. Thus, in reality, by measuring the dependence $I(B)$ [or $G(B)$] for a certain direction of B, we can find the shape of $|\Phi_{\mathrm{QD}}(k)|^2$ along the direction of k perpendicular to B. Then, rotating B in the (X, Y) plane and measuring $I(B)$ (in a sequence) for different orientations of B, we obtain the complete spatial profile of $|\Phi_{\mathrm{QD}}(k_x, k_y)|^2$, which is the projection of the probability density of a given electronic state of the quantum dot in the k-space in the plane perpendicular to the current [3].

Figure 4 depicts the profiles of differential conductance

$$G(B) = \frac{\mathrm{d}I}{\mathrm{d}V} \sim \left|\Phi_{\mathrm{QD}}(k_x, k_y)\right|^2$$

in the $(k_x,\ k_y)$ plane for the two quantum-dot states corresponding to Figs 3a, b. The resulting contour maps visualize the probability density distribution of the wave functions of the ground and excited states of a quantum dot. The electron wave functions are biaxially symmetric in the growth plane with the axes corresponding (to within measurement errors of about 15°) to the principal crystallographic

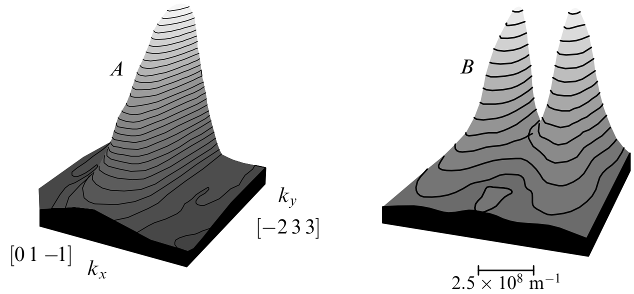

Figure 4. Profiles of the differential conductance, $G(B) = \mathrm{d}I/\mathrm{d}V \sim |\Phi_{\mathrm{QD}}(k_x, k_y)|^2$, in the $(k_x,\ k_y)$ plane for the two states of the quantum dots, corresponding to Figs 3a, b. The contour maps visualize the probability density distribution of the wave functions of the ground and excited states of a quantum dot.

directions X and Y for a (311) substrate orientation. For a (100) substrate we also obtained the characteristic images of the probability density for the ground and excited SAQD states.

The main result of the present work is a method that makes it possible to extract experimental information about the probability density distribution of the wave functions of electrons in self-assembled quantum dots. So far the proposed method is the only nondestructive technique for creating maps of the wave functions in SAQDs and has been applied to the given class of problems for the first time.

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References

1. Bimberg D, Grundmann M, Ledentsov N N *Quantum Dot Heterostructures* (New York: John Wiley, 1999)
2. Topinka M A et al. *Science* **289** 2323 (2000)
3. Vdovin E E et al. *Science* **290** 122 (2000)
4. Hayden R K et al. *Phys. Rev. Lett.* **66** 1749 (1991)
5. Beton P H et al. *Phys. Rev. Lett.* **75** 1996 (1995)
6. Sakai J-W et al. *Phys. Rev. B* **48** 5664 (1993)

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Tunneling spectroscopy of quasi-two-dimensional plasmons

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1. Introduction

In two-dimensional (2D) electron systems based on semiconductors with an isotropic, parabolic dispersion law, the electron motion along the interface and transverse to the interface separates. Hence, in a magnetic field B that is