Self-Induced Acoustic Transparency in Semiconductor Quantum Films

A. O. Govorov,[1,2,*] A. V. Kalameitsev,[1] V. M. Kovalev,[1] H.-J. Kutschera,[3] and A. Wixforth[3]

[1]*Institute of Semiconductor Physics, Russian Academy of Sciences, Siberian Branch, 630090 Novosibirsk, Russia*

[2]*Department of Physics and Astronomy, Ohio University, Athens, Ohio 45701*

[3]*Sektion Physik der Ludwig-Maximilians-Universität and Center for Nano-Science, Geschwister-Scholl-Platz 1, 80539 München, Germany*

(Received 13 March 2001; published 8 November 2001)

We develop a quantum theory of the nonlinear interaction between intense surface acoustic waves and electrons in a quantum well in the regime of moving quantum wires and dots. In the quantum nonlinear regime, the sound attenuation exhibits quantum oscillations and dramatically decreases with increasing quantization. In the case of dynamically created electron dots formed by two acoustic waves, the waves can propagate without any dissipation in the limit of high sound intensity and, hence, the electron quantum film acts as an acoustically quasitransparent material.

DOI: 10.1103/PhysRevLett.87.226803 PACS numbers: 73.50.Rb, 72.50.+b, 73.50.Fq

Electronic systems with reduced dimensionality and dramatically changed electron density of states due to the quantum confinement effect can be created in semiconductor crystals employing modern fabrication techniques. Prominent examples of such low-dimensional systems are quantum films (2D), quantum wires (1D), and quantum dots (0D). Compared to the classical bulk system (3D), all of the above low-dimensional systems have a considerably altered density of states. This fundamental property of low-dimensional electronic systems has technologically been exploited in the recent past. One of the best known examples is the semiconductor laser [1], in which the reduction in a density of states results in greatly improved characteristics [2].

Here, we demonstrate that also the acoustic properties of semiconductor nanostructures exhibit some very interesting and fascinating properties, which have no classical counterparts. Interestingly enough, one of the first theoretical considerations of low-dimensional effects in semiconductors was based on acoustically induced quantization and band structure effects [3], but so far, this approach has not been followed in great detail. In this Letter, we show how dramatically the acoustic transparency of mobile electrons changes when an acoustic wave creates dynamically defined 1D and 0D electron states from a formally homogeneous 2D quantum film.

When an acoustic wave propagates through a plasma of mobile electrons in a solid, it decays due to excitations in the continuum of electron states and also induces a "dragging" effect [4,5]. In application to semiconductor nanostructures, one of the most important mechanisms of the interaction between mobile electrons and sound originates from the piezoelectric (PE) effect. Presently, the acoustoelectric (AE) interactions involving the PE effect are studied in GaAs-based nanostructures mostly for the linear regime of small signals [6,7]. This is due to a weak piezoelectricity of GaAs. A greatly enhanced AE interaction has recently been observed in semiconductor-PE structures [8,9] which contain a semiconductor quantum well tightly bonded to a strongly PE host crystal (Fig. 1). The PE potential induced by a surface acoustic wave (SAW) in these hybrid structures is strong enough to break up an initially homogeneous electron plasma into moving wires. The strongly nonlinear phenomena observed in hybrid structures [9,10] at room temperature are well described by a nonlinear theory based on hydrodynamic equations [10,11]. However, for low temperatures, the

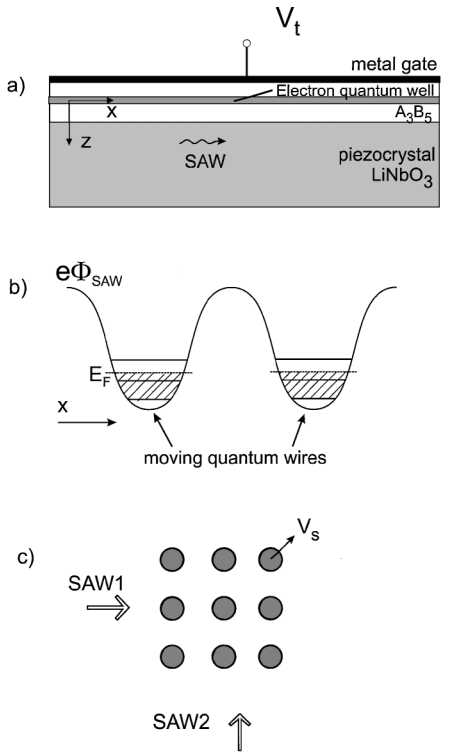

FIG. 1. (a) Cross section of a hybrid structure with traveling SAW's. The 2D electron density is controlled by the gate voltage V_t. (b) The moving PE potential of a SAW and the energy structure of moving quantum wires. (c) Sketch of a system with two SAW's and moving quantum dots (top view); $\mathbf{v}_s = (c_s, c_s)$ and c_s is the SAW velocity.

classical description can no longer hold because of the quantization induced by an intense SAW [3,12].

Here, we develop a quantum theory of the AE interaction in a 2D system for the strongly nonlinear regime of SAW-induced moving electron wires and dots. We show that the quantum AE interaction results in self-induced transparency for the transmission of surface acoustic waves. Along with a dramatic suppression of the sound dissipation we found the regimes of SAW intensities, where quantum oscillations in the SAW transmission can be observed. Our calculations were performed for realistic experimental parameters.

In our model, an intense SAW propagating along a 2D system of mobile electrons (Figs. 1a and 1b) dynamically creates moving quantum wires. Hence, in the presence of this intense SAW an initially homogeneous density of states of a 2D quantum well (Fig. 2a) turns into a 1D density of states, being strongly peaked at the quantization energies [13]. Further transformation into a quasi-zero-dimensional (0D) system is possible involving two SAW's [14] with perpendicular momenta (Fig. 1c). Here, the electron motion is confined in both in-plane directions and moving quantum dots with a fully quantized spectrum are dynamically created. In this case, the density of states is a set of delta functions. Thus, intense SAW's reduce the electron density of states from 2D toward 1D and even 0D (Fig. 2a).

A simple picture of the AE effects is as follows: The effective "friction" force for a sound wave originates from the dissipative electric current $\mathbf{j}_s$ in the plane of a quantum well induced by the PE field of a SAW. The electrons scatter by crystal defects, i.e., by impurities, and in such a way heat the crystal lattice. The sound energy dissipation per unit time and area is given by

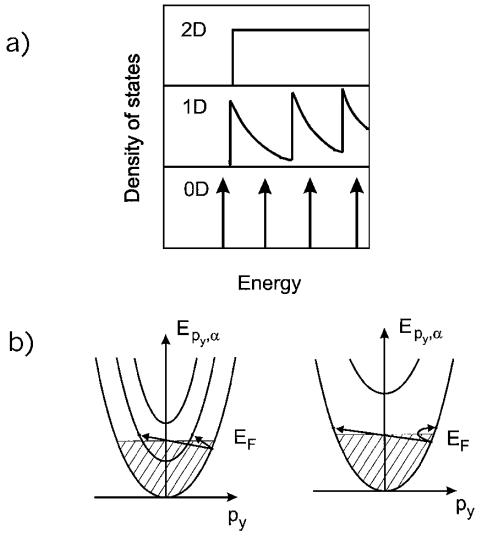

FIG. 2. (a) Density of states in 2D, 1D, and 0D electron systems. (b) Intersubband and intrasubband transitions induced by impurities in a moving 1D wire.

$$Q = \langle \mathbf{j}_s(\mathbf{r},t)\mathbf{E}_{\mathrm{SAW}}(x,t)\rangle_{\mathbf{r}}\,, \tag{1}$$

where $\langle \ldots \rangle_{\mathbf{r}}$ means averaging over surface area of a macroscopic sample and $\mathbf{E}_{\mathrm{SAW}}$ is the PE field induced by a SAW. $\mathbf{r} = (x, y)$ is the in-plane coordinate and t is the time. In our model, the Rayleigh SAW propagates in the x direction (Fig. 1a). The dissipative current $\mathbf{j}_s$ implies electron transitions in the continuum of states near the Fermi energy. The energy transfer in such transitions is small since the velocity of sound c_s is typically much less than the electron Fermi velocity v_F. So, these quasielastic transitions are possible only near the Fermi surface. Using this argument, we can conclude that in 2D and 3D systems the sound dissipation is quite effective because of the strong electronic scattering in the continuum of states near the Fermi level. The situation in 1D and 0D systems can be very different since the distribution of the density of states over the energy is strongly inhomogeneous (Fig. 2a). The sound attenuation can dramatically be suppressed when the density of states near the Fermi level becomes small (1D) or even vanishes (0D) and electrons near the Fermi level cannot scatter anymore.

We now consider the case when an intense SAW creates moving electron wires with a quantized energy spectrum in the x direction. It is convenient to discuss this problem using a moving coordinate system $(x' = x - c_s t, y)$, where the PE potential of the SAW appears to be static. Near its minima, we approximate this PE potential $\Phi_{\mathrm{SAW}} = \Phi^0_{\mathrm{SAW}} \cos(kx - \omega t) = \Phi^0_{\mathrm{SAW}} \cos(kx')$ by a parabolic function and consider a single wire for simplicity. Here, k and ω represent the sound momentum and frequency, respectively. The energy spectrum of a wire contains 1D subbands: $E_{p_y,n} = E_n + p_y^2/2m^*$, where $E_n = \hbar\Omega_0(n + 1/2)$, $\hbar\Omega_0$ is the quantization energy, n is the subband number, p_y is the momentum along a wire, and m^* is the effective electron mass. At relatively small intensity of sound, electrons occupy many 1D subbands and the system is quasi-2D with almost continuous density of states. In the latter case, the sound dissipation is expected to be high. The main contribution to the dissipation Q comes from quasielastic transitions between closely located subbands. However, the quantization energy increases with the PE potential: $\hbar\Omega_0 \propto \sqrt{\Phi^0_{\mathrm{SAW}}}$. For a fixed number of electrons and sufficiently high intensity of sound, the electrons fill only the few lowest subbands (Fig. 2b) and quantum effects start to play a major role. In this regime, the SAW dissipation basically reflects the density of states and oscillates with increasing Φ^0_{SAW}. Eventually, for the higher PE potential only the lowest subband becomes occupied by electrons (Fig. 2b) and transitions between subbands are no longer possible because of the quasielastic character of scattering. Nevertheless, intrasubband scattering (Fig. 2b) remains allowed even at very high SAW intensities. Thus, we see that the SAW dissipation cannot vanish even at very high sound intensity but the magnitude of dissipation

should strongly decrease. Such behavior of the calculated absorption in the regime of quantum wires is seen in Fig. 3. When $\Phi^0_{\rm SAW} > 0.5$ V, only residual intrasubband scattering remains possible and the absorption becomes saturated at its minimal value. Of course, the described phenomena are well expressed at low temperatures T.

To quantitatively describe the nonlinear quantum effects, we use a moving coordinate system (x', y), in which the random impurity potential becomes time dependent. We assume the Coulomb impurities to be distributed in space with a homogeneous 3D density, N_t. To find the electron current, we use the equation of motion for the single particle density matrix $\hat{f}$ within the framework of the self-consistent field approximation [15],

$$\frac{\partial \hat{f}}{\partial t} + \frac{i}{\hbar}[\hat{H}, \hat{f}] = \left(\frac{\partial \hat{f}}{\partial t}\right)_{\rm collisions}, \qquad (2)$$

where the Hamiltonian $\hat{H}$ includes the random impurity potential and the collision term describes weak electron-electron and electron-phonon interactions. Equation (2) can be solved in the framework of time-dependent perturbation theory regarding the impurity potential as a weak perturbation [16]. Then, we obtain the dissipation of a SAW in the form

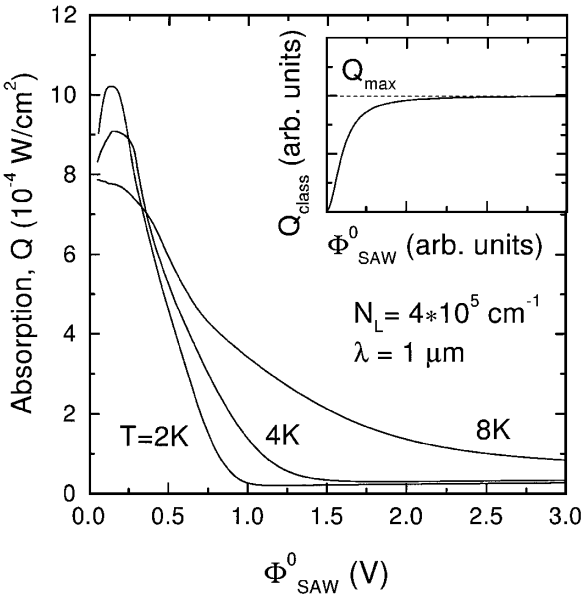

FIG. 3. Calculated SAW absorption in dynamically defined quantum wires as a function of the potential amplitude $\Phi^0_{\rm SAW}$ for various temperatures T. The parameters are given in the text. Inset: SAW absorption $Q_{\rm class}(\Phi^0_{\rm SAW})$ for a classical electron system at room temperature.

$$Q = \frac{N_t}{\lambda(2\pi)^2\hbar}\sum_{n,n'}\int dq_x dq_y\, D_{n,n'}(q_y, c_s q_x)\,|A_{n,n'}(q_x)|^2\langle|U_0(q_x, q_y, Z_i)|^2\rangle_{Z_i}\int dp_y\, c_s q_x (f^0_{p_y,n} - f^0_{p_y+q_y,n'}) \times \delta(\hbar c_s q_x + E_{p_y,n} - E_{p_y+q_y,n'}), \qquad (3)$$

where $A_{n,n'}(q_x) = \int dx\, \psi_n(x)\psi_{n'}(x)e^{iq_x x}$, $\psi_n(x')$ is the electron wave function in a wire; $U_0(q_x, q_y, Z_i)$ is the 2D Fourier transform of the single impurity potential with the vertical coordinate Z_i and $\langle\ldots\rangle_{Z_i}$ means averaging over Z_i; $f^0_{p_y,n}$ is the Fermi distribution function and $D_{n,n'}(q_y, \omega)$ is the screening factor. For our numerical calculations (Fig. 3) we used the following parameters: the wavelength $\lambda = 1$ μm, $c_s = 3.9 \times 10^5$ cm/s, the 1D electron density $N_L = 4 \times 10^5$ cm^{-1}, $N_s = N_L/\lambda = 4 \times 10^9$ cm^{-2}, $N_t = 4.1 \times 10^{14}$ cm^{-3}, and $m^* = 0.07m_0$. The parameter N_t is found from the low-temperature mobility of a 2D homogeneous gas, μ_{2D}; $\mu_{2D} = 3 \times 10^6$ cm^2/V s at the 2D density $N_s = 3 \times 10^{11}$ cm^{-2}. Also, we have neglected the weak electron-phonon scattering assuming the low-temperature regime [1,12]. Equation (3) has a clear sense and describes impurity-induced transitions between various states in a quantum wire (Fig. 2b). It reproduces the physical picture described above very well.

The quantum picture of the AE interaction is significantly changed from the classical one. At room temperature, the absorption is an increasing function of $\Phi^0_{\rm SAW}$ and becomes saturated for high sound intensities in the regime when a SAW totally traps all electrons into wires (Fig. 3 inset) [10,11]. For the typical room-temperature parameters $\mu_{2D} = 5000$ cm^2/V s and $N_s = 4 \times 10^9$ cm^{-2} [9], we obtain $Q_{\rm max} \simeq 2 \times 10^{-2}$ W/cm^2 which is a few orders of magnitude larger than the calculated quantum-limit absorption.

In the case of dynamically created quantum dots, the effect of the quantization is even stronger as the density of states can vanish near the Fermi level and any quasielastic transitions become impossible at sufficiently high sound intensity. We now consider two perpendicular sound waves, SAW1 and SAW2, producing PE potentials $\Phi^0_{\rm SAW1(2)}$ (Fig. 1c). A quantum dot created by the SAW's can be regarded as a 2D anisotropic harmonic oscillator with two frequencies: $\Omega_{\rm SAW1(2)} \propto \sqrt{\Phi^0_{\rm SAW1(2)}}$. Calculations for the case of quantum dots are very similar to those related to the wires [16]. For the symmetric case $\Phi^0_{\rm SAW1} = \Phi^0_{\rm SAW2} = \Phi^0_{\rm SAW}$, the asymptotic behavior for the absorption of both SAW's is

$$Q_{\rm tot} \propto e^{-(\hbar\Omega_0/2m^*c_s^2)} = e^{-\sqrt{\Phi^0_{\rm SAW}/\Phi_s}}, \qquad (4)$$

where $\Omega_0 = \Omega_{\rm SAW1(2)}$, $\Phi_s = 4(m^*c_s^2)^2 \times m^*/[e\hbar^2k^2]$, and $\Phi^0_{\rm SAW} \to \infty$. In the limit of large SAW intensities, the absorption decreases exponentially. The latter is based on the inequality $\hbar c_s/l_0 \ll \hbar\Omega_0$, where $l_0 = \sqrt{\hbar/m^*\Omega_0}$. The effect of quantization on the SAW absorption is really drastic (Fig. 4). The maximal PE potentials achieved for

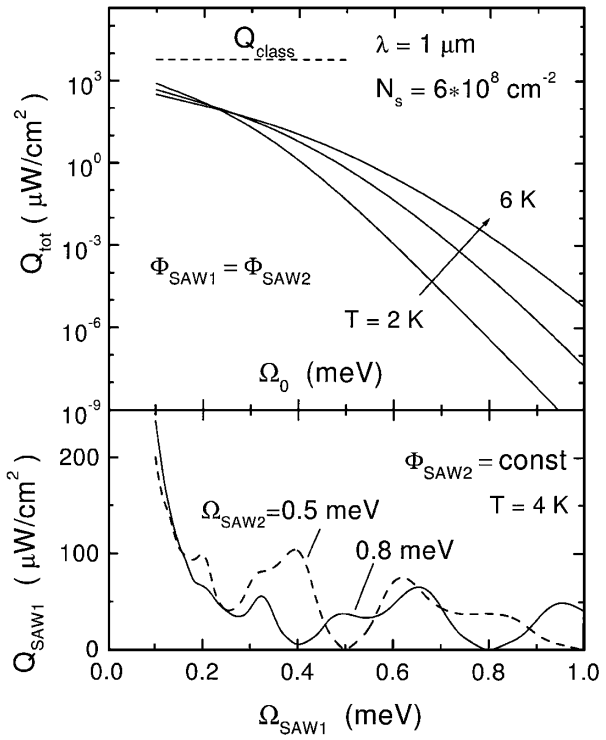

FIG. 4. Calculated absorption of both SAW's Q_{tot} for dynamically defined quantum dots as a function of the sound-induced lateral quantization Ω_0 for the equal intensities of SAW's. The lower part shows the absorption of the SAW1 for fixed intensity of the SAW2.

hybrid and GaAs structures are about 1–2 V corresponding to $\hbar\Omega_0 \sim 1$ meV [9,14]. The calculated absorption for $\hbar\Omega_0 \sim 1$ meV at temperature $T = 2$ K turns out to be 12 orders of magnitude smaller than the one at room temperature. For the asymmetric case $\Phi^0_{\text{SAW1}} \neq \Phi^0_{\text{SAW2}}$, we find the regime of the quantum interaction between SAW's and giant quantum oscillations (Fig. 4).

Experimentally, the electron density in a quantum well can be controlled by a voltage applied to a metal top gate (Fig. 1a) [9] or optically induced [14]. Also, an important question related to experiments is the heating effect. By solving the energy balance equation, we showed that the heating effect is weak in high-quality quantum wells with a mobility above about 10^6 cm^2/V s and that the low-temperature solution is stable [16].

To conclude, we have described novel quantum phenomena in the nonlinear propagation of intense surface acoustic waves through an electron plasma. A dynamical reduction of the density of states in an electron plasma results in a dramatic decrease of the sound dissipation. Modern hybrid structures can be candidates to experimentally observe the predicted quantum transparency effect for sound waves.

We thank J. P. Kotthaus for important motivating remarks and B. Laikhtman, A. V. Chaplik, I. L. Drichko, and A. Mayer for helpful discussions. We gratefully acknowledge financial support by Ohio University, by the Volkswagen-Foundation, and by the RFBR (Russia).

*Email address: govorov@helios.phy.ohiou.edu

[1] S. M. Sze, *Physics of Semiconductor Devices* (John Wiley and Sons, New York, 1981).
[2] N. Kirstaedter *et al.,* Electron. Lett. **30**, 1416 (1994); H. Cao *et al.,* Appl. Phys. Lett. **76**, 3519 (2000); P. Michler *et al., ibid.* **77**, 184 (2000).
[3] L. V. Keldysh, Fiz. Tverd. Tela (Leningrad) **4**, 1015 (1962).
[4] R. H. Parmenter, Phys. Rev. **89**, 990 (1953); G. Weinreich, T. M. Sanders, and H. G. White, Phys. Rev. **114**, 33 (1959).
[5] M. J. Hoskins, H. Morko, and B. J. Hunsinger, Appl. Phys. Lett. **41**, 332 (1982); W. J. Tanski *et al., ibid.* **52**, 18 (1988).
[6] A. Wixforth *et al.,* Phys. Rev. B **40**, 7874 (1989); R. L. Willett *et al.,* Phys. Rev. Lett. **71**, 3846 (1993); V. I. Talyanskii *et al.,* Phys. Rev. B **56**, 15 180 (1997); I. L. Drichko *et al.,* Phys. Rev. B **62**, 7470 (2000).
[7] A. V. Chaplik, Pis'ma Zh. Tekh. Fiz. **10**, 1385 (1984) [Sov. Tech. Phys. Lett. **10**, 584 (1984)]; V. L. Gurevich, V. B. Pevzner, and G. J. Iafrate, Phys. Rev. Lett. **77**, 3881 (1996); A. D. Mirlin and P. Wölfle, *ibid.* **78**, 3717 (1997); Y. Levinson *et al.,* Phys. Rev. B **58**, 7113 (1998); C. Eckl, Yu. A. Kosevich, and A. P. Mayer, *ibid.* **61**, 16 708 (2000); G. R. Aizin, G. Gumbs, and M. Pepper, *ibid.* **58**, 10 589 (1998).
[8] M. Rotter *et al.,* Appl. Phys. Lett. **70**, 2097 (1997).
[9] M. Rotter *et al.,* Phys. Rev. Lett. **82**, 2171 (1999); M. Rotter *et al.,* Appl. Phys. Lett. **75**, 965 (1999).
[10] A. O. Govorov *et al.,* Phys. Rev. B **62**, 2659 (2000).
[11] V. L. Gurevich and B. D. Laikhtman, Zh. Eksp. Teor. Fiz. **46**, 598 (1964) [Sov. Phys. JETP **19**, 407 (1964)]; P. K. Tien, Phys. Rev. **171**, 970 (1968); Yu. V. Gulyaev, Fiz. Tverd. Tela (Leningrad) **12**, 415 (1970) [Sov. Phys. Solid State **12**, 328 (1970)].
[12] B. D. Laikhtman and Yu. V. Pogorel'skii, Zh. Eksp. Teor. Fiz. **75**, 1892 (1978) [Sov. Phys. JETP **8**, 953 (1978)].
[13] J. H. Davies, *The Physics of Low-Dimensional Semiconductors* (Cambridge University Press, Cambridge, U.K., 1998).
[14] C. Rocke *et al.,* Phys. Rev. B **57**, R6850 (1998); M. Streibl *et al.,* Appl. Phys. Lett. **75**, 4139 (1999); F. Alsina *et al.,* Phys. Rev. B **64**, 041304(R) (2001).
[15] M. P. Greene *et al.,* Phys. Rev. **177**, 1019 (1969).
[16] A. O. Govorov, A. V. Kalameitsev, and V. M. Kovalev, cond-mat/0101227.