Stretching quantum wells: A method for trapping free carriers in GaAs heterostructures

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We have demonstrated a method of using inhomogeneous stress to create an in-plane harmonic potential in GaAs quantum wells which works equally well for excitons and for free conduction electrons. The depth of the well can be continuously varied via an external control. This essentially provides a type of gate for controlling the motion of carriers, e.g., a two-dimensional electron gas, without using electric field. © *1999 American Institute of Physics.* [S0003-6951(99)00940-7]

More than twenty years ago, a method of using stress to control the motion of carriers was demonstrated in bulk semiconductors,[1–3] which could be used to trap excitons in a harmonic potential minimum. The question naturally arises whether a similar method could be used to trap carriers in two dimensions, in particular in GaAs quantum wells. We have found that inhomogeneous applied stress can be used to create a harmonic potential in GaAs quantum wells for both excitons and free electrons in the conduction band, but that this result does not primarily arise from the effect of *shear* stress, as in the case of the bulk semiconductor experiments, but rather, it arises from a *hydrostatic expansion*, i.e., a ''stretching'' of the sample, in a special geometry.

In the experiments on bulk semiconductors, the primary effect of the applied stress was to create a shear stress maximum. The shear stress acted to split the degeneracy of certain electronic bands, shifting one band to lower energy and therefore creating an energy minimum for the excitons. The uniaxial stress used in the experiments also created a hydrostatic compression, but in the semiconductors chosen (Ge,[1] Si,[2] and Cu_2O[3]) the upward energy shift of the bands due to the hydrostatic deformation was small compared to the contribution of the shear term.

In GaAs, it is well known that the hydrostatic deformation term is much larger than the shear deformation potential term,[4] so that the above experiments cannot be done on excitons in bulk GaAs—the shift of the conduction band upward due to compression in uniaxial stress overwhelms the small shift downward due to splitting of the valence band degeneracy. The same is true in quantum heterostructures. Therefore the only ways to use stress to create an energy minimum in GaAs for free carriers are either to induce a stress with no hydrostatic term, i.e., a traceless stress, or to induce a hydrostatic expansion, or stretching, in which case the hydrostatic deformation potential gives a shift to lower energy. We have accomplished the latter. In our experiments we analyzed the stresses using exciton luminescence, but because the main effect arises via the conduction band hydrostatic deformation potential, the method should also apply to free electrons, e.g., in the two-dimensional electron gas (2DEG).

The samples we used were GaAs/$Al_xGa_{1-x}As$ coupled quantum well structures fabricated via molecular-beam epitaxy (MBE). To improve the contact with the stressor, both sides of the substrate were polished before the heterostructure was grown by MBE. Five sets of coupled quantum wells were created which consisted of two 60 Å undoped GaAs wells with a 42 Å $Al_{0.3}Ga_{0.7}As$ barrier between them, with 200 Å pure AlAs barriers in between the sets of coupled quantum wells. We observed the luminescence emitted by excitons formed from the lowest conduction subband and the highest (heavy hole) valence subband in these quantum wells. At low temperature and low excitation density, the inhomogeneous broadening of the exciton luminescence has a full width at half maximum of about 1 meV.

Figures 1 and 2 show the theoretical and experimental results for two different stress geometries. In Fig. 1, the sample is suspended freely over a circular hole in a lower plate, and the back side of the substrate is pressed with a needle ($\sim 50\,\mu m$ contact area) which contacts the sample through a circular hole in the upper clamping plate, as illustrated in the inset of Fig. 1(a). This allows the sample to bend and therefore induces a slight stretching of the sample. The assembly is placed in liquid helium, and the force on the needle is controlled by a micrometer at the top of the cryostat, as in Ref. 2. Too much stress from the pin will cleave the sample, of course, but springs on the lower plate help to prevent this, allowing a reproducible, controllable stress. The exciton luminescence is excited and observed from below, through the hole in the bottom plate. The image in Fig. 1(b) shows time-integrated luminescence from a coupled quantum well sample taken with a CCD camera on the back of an imaging spectrometer as the laser spot is scanned across the surface of the sample. As seen in this image, the energy of the excitons decreases to a minimum directly under the pin. A well depth of more than 5 meV is created, compared to the inhomogeneous broadening in these samples of around 1 meV.

In Fig. 2, the sample is placed face down on a glass slide and pressed with a needle, as illustrated in the inset of Fig. 2(a). The exciton luminescence is excited and observed from below, through the glass slide. As seen in Fig. 2(b), which is

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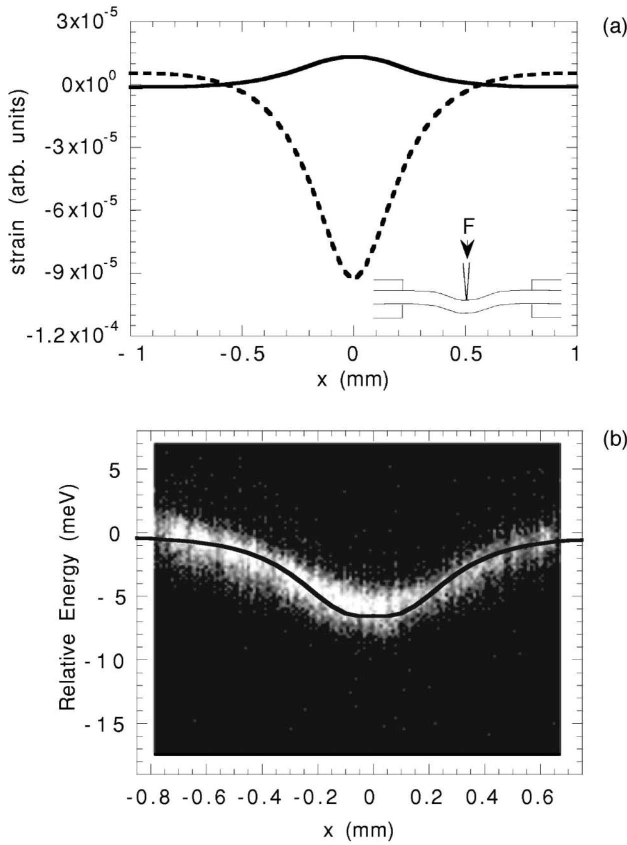

FIG. 1. (a) Inset: Illustration of the stress geometry with unconstrained bottom. Solid line: Numerical solution for the hydrostatic strain ($\epsilon_{xx}+\epsilon_{yy}+\epsilon_{zz}$) on the bottom surface of the sample (in the plane of the quantum wells) in this geometry, for the elastic constants of GaAs (Ref. 4) (the slightly different elastic constants of AlAs used in the quantum well barriers are not taken into account). Dashed line: the shear strain ($2\epsilon_{zz}-\epsilon_{xx}-\epsilon_{yy}$). The substrate thickness is 500 μm, and the hole diameter is 2.5 mm. (b) Time-integrated image of the exciton luminescence from the quantum wells, taken with a CCD camera on an imaging spectrometer, as the laser spot is scanned across the bottom surface of the sample in the stress geometry shown in the inset of (a). The energy $E=0$ corresponds to the photon energy 1.614 eV, from the heavy-hole excitons in a 60 Å quantum well. The solid line superposed on the data is the shift in energy given by the Hamiltonian [Eq. (1)] for the strain field shown in (a) and the values of the deformation potentials for GaAs given in the text.

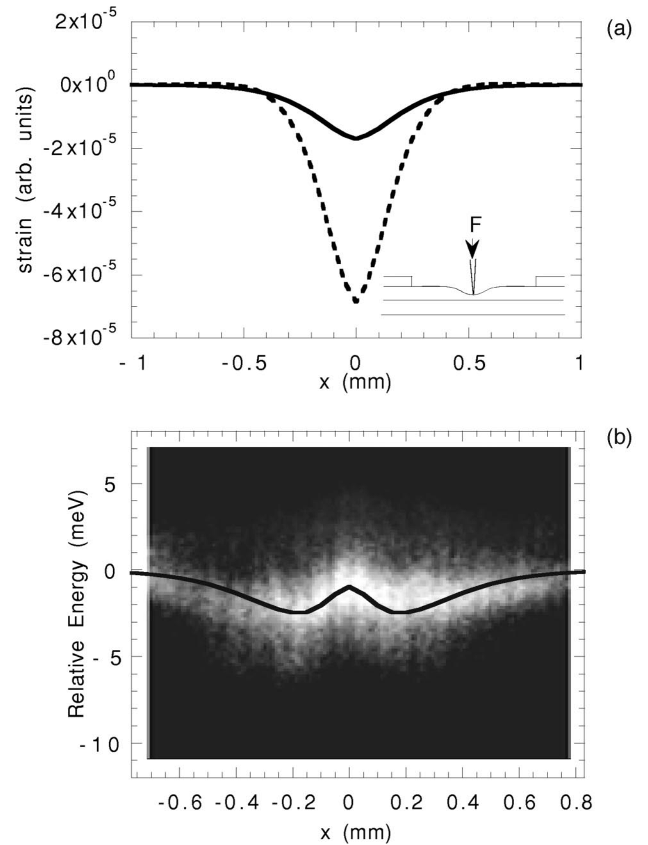

FIG. 2. (a) Inset: Illustration of the stress geometry with constrained bottom, in which the sample is placed on a glass slide. Solid line: Numerical solution for the hydrostatic strain ($\epsilon_{xx}+\epsilon_{yy}+\epsilon_{zz}$) in this geometry. Dashed line: the shear strain ($2\epsilon_{zz}-\epsilon_{xx}-\epsilon_{yy}$). (b) Time-integrated image of the exciton luminescence from the quantum wells, taken by the same method as (b), in the stress geometry shown in the inset of (a). The solid line superposed on the data is the shift in energy given by the Hamiltonian [Eq. (1)] for the strain field shown in (a) and the values of the deformation potentials for GaAs given in the text.

recorded with a CCD camera on an imaging spectrometer in the same way as Fig. 1(b), in this case there is an energy *maximum* directly below the pin.

The theory curves shown in Figs. 1(a) and 2(a) show why this happens. These figures show the numerical solutions for the hydrostatic and shear components of the stresses induced in the plane of the quantum wells in these two different geometries, from a three-dimensional finite element calculation using the three elastic constants of GaAs. The details of this calculation will be presented elsewhere.[5] As seen by comparison of these two plots, both geometries induce a large shear stress, but the sign of the hydrostatic term is the opposite in the two different cases. Therefore in the stress geometry of Fig. 1, the hydrostatic deformation potential gives a negative term which contributes to the energy minimum, while in the stress geometry of Fig. 2, the hydrostatic deformation potential gives a positive term which nearly cancels the shear term.

The theory curves plotted over the data in Figs. 1(b) and 2(b) show that the experimental results are consistent with previous measurements of the deformation potentials in GaAs. The energy shift of the bands due to strain is given by the Pikus and Bir deformation Hamiltonian:[6]

$$H_{\rm PB}=a(\epsilon_{xx}+\epsilon_{yy}+\epsilon_{zz})+3b[(J_x^2-J^2/3)\epsilon_{xx}+\text{c.p.}]$$
$$+\frac{6d}{\sqrt{3}}\left[\frac{1}{2}(J_xJ_y+J_yJ_x)\epsilon_{xy}+\text{c.p.}\right], \qquad (1)$$

in which *a, b*, and *d* are the deformation potentials, the ϵ_{ij} are the strain tensor components, and the *J*'s refer to the spin states of the valence band, $m=3/2$, 1/2, $-1/2$, and $-3/2$. For a uniaxial strain along the *z* direction, this Hamiltonian corresponds to $E_{\rm PB}=3a\epsilon_{\rm hydro}\pm 3b\epsilon_{\rm shear}$, where $\epsilon_{\rm hydro}=\frac{1}{3}(\epsilon_{xx}+\epsilon_{yy}+\epsilon_{zz})$, and $\epsilon_{\rm shear}=(\epsilon_{zz}-\frac{1}{2}\epsilon_{xx}-\frac{1}{2}\epsilon_{yy})$. When the geometry is not purely uniaxial, as in the present experiments, the Hamiltonian Eq. (1) gives a 4×4 matrix for the energy eigenstates which must be diagonalized into two doublet states at each point in space. Because we observe the luminescence of excitons which are confined in quantum wells, we are concerned only with the lower doublet, i.e. the heavy-hole excitons. The curves plotted in Figs. 1(b) and 2(b) are these eigenvalues, calculated from the strain field shown in Figs. 1(a) and 2(a), respectively, using the values of $a=-7$ eV, $b=2$ eV, and $d=5.5$ eV. These lie within the ranges previously measured,[4] $a=-(7-10)$ eV, *b*

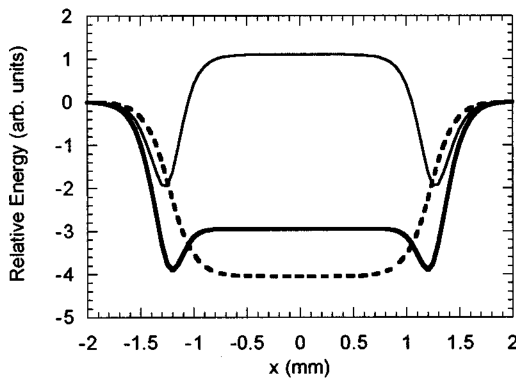

FIG. 3. Light solid line: the total energy shift of the exciton energy from the Hamiltonian [Eq. (1)] for the strain field which arises when a distributed force (a 2 mm diameter circle) instead of a point force is applied to the top surface of the sample in the constrained stress geometry shown in the inset of Fig. 2(a), for GaAs. Heavy solid line: the contribution of the shear b and d terms in the Hamiltonian [Eq. (1)] alone. Dashed line: the contribution of the hydrostatic a term in the Hamiltonian [Eq. (1)] alone.

$=(1.7-2)$ eV, and $d=(4.5-5.5)$ eV. We find a slightly better fit of the data with the values listed above, but if the values of *a, b*, and *d* are varied within these ranges, the data can still be fit reasonably well, and therefore while these experiments provide a confirmation of the above ranges of the deformation potentials, they do not provide an additional constraint.

It is well known that a purely uniaxial stress gives a net upward shift of the gap in GaAs.[7] How is it then that not only the case of Fig. 1 but also the case of Fig. 2, which involves a quasiuniaxial compression, gives an overall downward shift in the exciton luminescence? Figure 3 shows how this comes about. This figure shows the relative contribution of the energy terms in Eq. (1), for a numerical calculation of the strain field in the case of a distributed load of radius 1 mm instead of a point force, with the bottom surface constrained as in the geometry of Fig. 2. As seen in Fig. 3, in the central region where the strain field is nearly uniaxial, the hydrostatic term dominates and the overall shift of the energy is positive. Near the edges, the shear terms dominate and the overall shift is negative. This is a general effect. We have seen that when a blunt stressor is used when pressing the sample against a glass slide instead of a sharp pin, the energy shift of the excitons is characterized by an overall upward shift with sharp negative features at the edges.

Previous experiments (see, e.g., Ref. 8 and references therein) have shown that the hydrostatic deformation potential arises mostly from the conduction band. Intuitively, this makes sense if one thinks of the hydrostatic deformation potential primarily as due to the volume change of the unit cell, which would cause the light conduction electrons to shift much more strongly than the heavy holes. This implies that the geometry of Fig. 1 should work well to produce an energy minimum for free conduction-band electrons in two dimensions, i.e., the 2DEG, since the hydrostatic stretching term will give a negative shift even in the absence of a shear term. There is no analogous method for trapping free electrons in bulk semiconductors, since it is difficult to create a large hydrostatic expansion in a bulk material.

The ability to control the volume of a gas of excited carriers in a semiconductor heterostructure opens the door to numerous possibilities for studying electronic phase transitions in two dimensions. Previously, traps for carriers in bulk semiconductors have been used to study phase transitions between electron-hole liquid, free exciton gas, and excitonic molecules,[9] but phase transitions of these types have not been studied in two dimensions. Traps for excitons in two dimensions have also been proposed[10] as a method of observing Bose condensation of excitons. While fast transport[11,12] and other statistical effects which suggest Bose effects[13,14] have been observed in excitons and excitonic molecules in two-dimensional structures, in those experiments the volume occupied by the carriers was not well defined. By trapping the carriers in a well-defined volume, nonequilibrium transport effects can be minimized. Considerations for using these traps for Bose condensation of indirect excitons are reported elsewhere.[15]

Our calculations[5] show that the radius of the energy minimum seen in Fig. 1 scales primarily with the thickness of the substrate. Therefore one can easily imagine producing smaller traps by thinning the substrate. While these traps probably cannot be made as small or as deep as quantum dots, they have the advantage that they are completely reversible and removable, since the depth of the trap is determined by an external control during the experiment.

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