Plasmons in a superlattice in a parabolic quantum well

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Well-defined plasma oscillations are observed in a superlattice miniband even though the Fermi energy lies in the minigap. Despite the complex band structure, the resonance shows a remarkable insensitivity to changes in the number of electrons in the parabolic well in which the superlattice is placed, a feature of the generalized Kohn theorem that is expected only in the limit that the Fermi energy is near the bottom of the lowest miniband. © *1995 American Institute of Physics.*

Infrared filters, emitters, and modulators, that are based on electron intersubband transitions in parabolic quantum wells (PQWs) have a fixed resonance frequency (determined by the curvature of the empty parabola) which is insensitive to doping variations and bias conditions. In contrast to the usual case of square quantum wells, this is a consequence of the generalized Kohn theorem.[1–5] Along with the curvature, another way to control the built-in resonance frequency is to make the electrons heavier by the insertion of a superlattice (SL) within the well. We report in this letter that this control can be experimentally achieved while still maintaining the simple resonance spectrum of the parabolic well.

A numerical analysis of optical absorption in such a well by Brey *et al.*[6] shows a critical parameter to be the position of the Fermi energy E_F with respect to the lowest miniband calculated for the SL (assumed infinite). When E_F is near the bottom of the miniband the generalized Kohn theorem holds with a renormalized electron mass $m^*=m_{SL}$, the miniband edge mass. As E_F moves up the miniband and into the minigap, nonparabolicity effects become important, m^* increases, the main resonance frequency drops dramatically, strong satellite peaks appear, and the resonance is expected to depend on the number of electrons (n_s) in the well. The theorem is violated.

However, an experiment which changes n_s in one such well does not cause E_F to move across the miniband. E_F is nearly pinned by the average three-dimensional (3D) density determined by the curvature of the parabola. As more electrons are added to the well, E_F does *not move up*. Rather, more miniband states drop below it. This is because the extra electrons are added to the edges of the starting distribution occupying more SL periods.[7] We anticipate that, for a given well, if the curvature-determined E_F were to lie near the top of the miniband or in the minigap, an n_s-dependent complex absorption spectrum, a signature of the theorem's violation, would be observed.

To allow a direct observation of the effect of a SL on the optical absorption of a PQW, two samples were studied: PB31, a 2000 Å wide PQW with the Al mole fraction $x_{Al(z)}$ graded quadratically from 0 at the center to 0.2 at the edges [Fig. 1(a)] sandwiched between $Al_{0.3}Ga_{0.7}As$ barriers, and PB32, identical to PB31 in every respect, with the addition to the PQW of a square SL of period 200 Å, barrier width 40 Å and Al mole fraction barrier height $\Delta x_{Al}=0.1$ [Fig. 1(b)]. The distribution of the 3D electron density $n_0(z)$ in the wells were extracted from capacitance–voltage ($C-V$) measurements between a front gate and the ohmically contacted three-dimensional electron gas 3DEG[8,9] (Fig. 1). As expected, $n_0(z)$ is seen to be approximately constant at the curvature value $\sim 2.6\times 10^{16}$ cm^{-3} for the PQW [Fig.

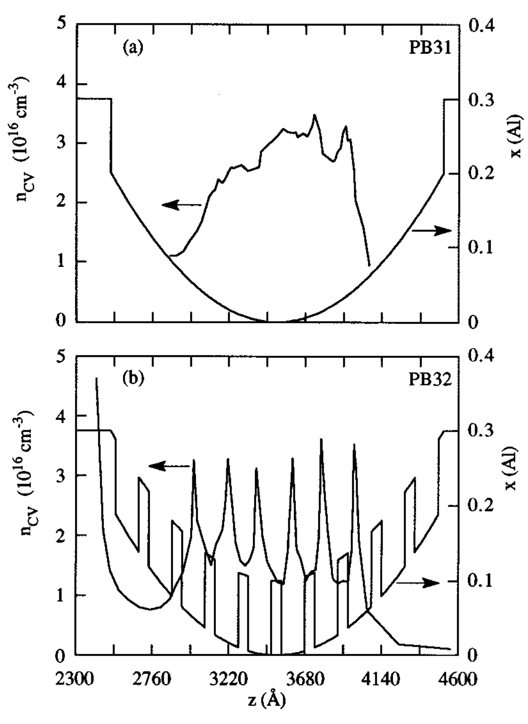

FIG. 1. (a) Three-dimensional electron density distribution in a parabolic well (Al mole fraction profile also shown) at $T=4.2$ K from $C-V$ measurements. (b) Three-dimensional electron distribution in parabolic well with 200 Å period superlattice superimposed (Al mole fraction profile shown) showing density modulation produced by superlattice.

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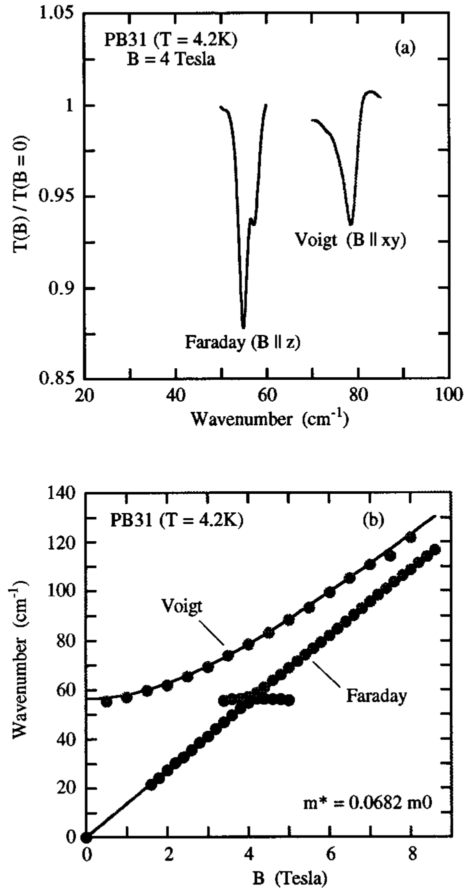

FIG. 2. (a) Cyclotron resonances at Faraday and Voigt geometries for electrons in parabolic well at $B=4$ T, showing the plasma frequency shift between the two. The splitting in the CR peak for the Faraday geometry is due to the slight coupling between the CR and the plasma resonance due to the sample wedge. (b) CR peak positions vs magnetic field. Lines are calculated curves. The additional peaks around $B \sim 4$ T are due to the coupling between the CR and the plasma resonance.

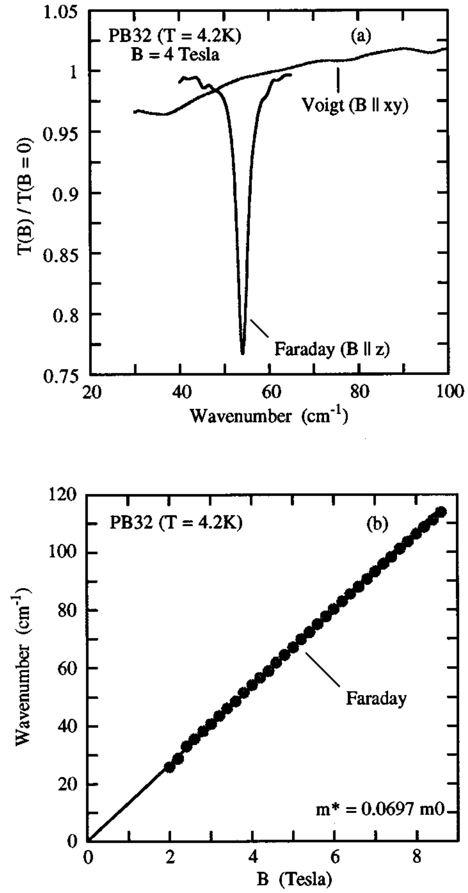

FIG. 3. (a) Cyclotron resonance in Faraday geometry for electrons in parabolic well with superlattice at $B=4$ T. No absorption is observed in Voigt geometry in any field up to 8.6 T. (b) CR peak positions vs magnetic field.

1(a)]. It is measured to be strongly modulated for the parabolic well with superimposed SL [Fig. 1(b)], the modulation period being equal to the SL period of 200 Å, and the *average* density being close to the curvature value of the underlying parabola.

Cyclotron resonance (CR) measurements on the electrons in the PQW at $T=4.2$ K in the Faraday geometry (magnetic field B parallel to z) reveal resonances whose positions obey the relation $\omega=\omega_c=eB/m^*$, with $m^*=0.0682m_0$, where m_0 is the free-electron mass (Fig. 2). A small splitting of the resonance around $\omega \sim 56.4$ cm $^{-1}$ is due to the coupling of the CR with the plasma or intersubband resonance of the electrons in the well due to the small ($\sim 2°$) sample wedge.[5] In the Voigt geometry (magnetic field B perpendicular to z), a plasma shifted cyclotron resonance (PSCR) is observed that obeys the relation $\omega^2=\omega_0^2+\omega_c^2$ (Fig. 2) where $\omega_0 \sim 56.4$ cm^{-1}. This compares well with the calculated harmonic oscillator (HO) frequency of $\sim$ 50 cm^{-1} for the bare parabola, which by construction is equal to the plasma frequency $\omega_p=(e^2 n_0/\epsilon m^*)^{1/2}$ of a 3DEG with uniform density n_0, where n_0 corresponds to the curvature of the parabola.[3,5]

For the PQW with superimposed SL, a sharp CR absorption is observed in the Faraday geometry [Fig. 3(a)]. The in-plane mass of the electrons extracted from the resonance is $m^* \sim 0.0697m_0$ [Fig. 3(b)], slightly higher than the in-plane electron mass in the parabolic well. However, no absorption is observed in the Voigt geometry at any magnetic field. An in-plane field would launch the electrons in cyclotron orbits in a plane where an electron has to tunnel through the superlattice to complete its orbit. The diameter of the tightest orbit ($B_{\rm max}=8$ T) in our experiment is $2R_c = 2(\hbar/eB)^{1/2} \sim 181$ Å, implying that we never reach a field high enough to confine the cyclotron orbit entirely inside the 160 Å wide well of the SL. Hence, we do not observe any completely bound orbits. Nor do we observe any barrier-pinned orbits, in contrast to similar experiments on modulation-doped square superlattices.[10–12] The Voigt geometry CR would occur at a frequency determined by the geometric mean of the in-plane mass and the SL miniband mass. The latter mass is determined to be $\sim$4 times the former (see below). At 8 T this gives a Voigt geometry CR at 53.6 cm^{-1}. Correction by the plasma frequency of 21 cm^{-1} (see below) yields an observable plasma shifted cyclotron resonance at 57.6 cm^{-1} at 8 T. Its absence suggests that the PSCR has perhaps been broadened out by a distribution of orbits from those pinned at the centers of the barriers to those pinned at the centers of the wells.[10–12]

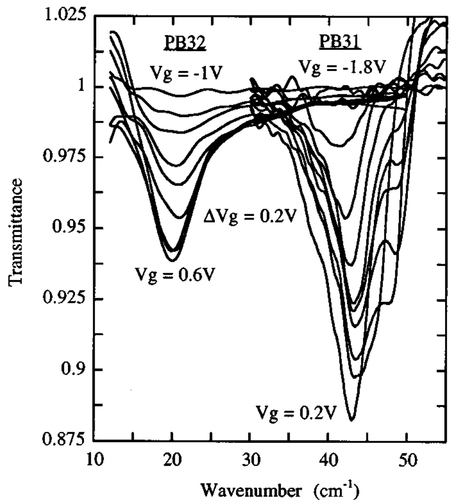

FIG. 4. Relative transmittances through the two wells in a slab geometry experiment at various gate biases show resonant absorption at the bare (HO) frequency for the parabolic well (PB31) and resonant absorption at the HO frequency redshifted by the superlattice for the parabolic well with superlattice (PB32). Both resonances are approximately independent of the number of electrons (i.e., the gate bias) in the wells. The noise at either end of the spectral range is due to the reduced transmission of the 50 μm beamsplitter at these ends.

To directly excite these plasma resonances requires the electric field of the incident radiation to have a component polarized parallel to the growth direction. Hence, the unpolarized FIR light from a spectrometer was focused on the edge of the sample and sent edgewise through it to a bolometer. The path length was ~4 mm. Front gates were used to tune the number of electrons in the wells from 0 to $\sim 5\times 10^{11}$ cm^{-2} as measured by $C-V$ measurements. The transmittance spectra are calculated as $T(V_g)/T(V_g<V_T)$, where $T(V_g)$ is the transmission through the sample at a gate voltage V_g, and $T(V_g<V_T)$ is the transmission at a gate voltage well beyond the threshold voltage V_T required to deplete all electrons out of the well.

Figure 4 shows the transmittance spectra for both wells. In accordance with the generalized Kohn theorem, the electrons in the PQW show absorption at approximately the same frequency independent of the number of electrons (i.e., the gate voltage). The main resonance frequency is ~42 cm^{-1}, to be compared with the calculated value of ~50 cm^{-1}.

Of most interest is the resonance observed in the transmittance traces for the electrons in the parabolic well with SL (Fig. 4). A clear resonance is measured at all gate biases. Within the experimental resolution of 1 cm^{-1}, it is approximately independent of the number of electrons in the well. The generalized Kohn theorem apparently continues to hold. The oscillator strength is reduced by half compared to that for the PQW though the n_s and optical coupling geometries are similar: We attribute this mostly to a transfer of some of the oscillator strength from the collective plasma resonance to interminiband transitions in the SL. Also, the resonance frequency has moved to ~21 cm^{-1}, i.e., half the value for the parabolic well. This implies an increase in m^* by a factor of 4. This is ~2.4 times higher than the miniband edge mass $m_{\rm SL}$ calculated to be 1.64 m_0 from a Kronig–Penney analysis of the square superlattice (assumed infinite). The SL miniband width is calculated to be ~4.7 meV. The Fermi energy is calculated to be ~4.8 meV above the lowest miniband state as determined by the curvature of the parabola. A self-consistent Poisson–Schrödinger calculation at the maximum electron density $n_s \sim 5\times 10^{11}$ cm^{-2} in the well, pins E_F at ~3.9 meV above the lowest occupied state. These two estimates place E_F either in the first minigap or near the top of the lowest miniband. Yet, a single resonance is observed, with its frequency nearly independent of n_s, i.e., the generalized Kohn theorem is not violated even in this extreme limit. It is possible that the conclusions drawn by Brey *et al.*[6] depend on the particular well design parameters used in their calculations. A calculation of the optical absorption for our wells as a function of n_s, using the techniques outlined by them, may yield the experimental results we observe.

In conclusion, the addition of a superlattice produces a large redshift in the collective plasma resonance of the electrons in a PQW. This shift is entirely accounted for by the increased electron mass due to the SL. The frequency is nearly constant down to the last few electrons as the number of electrons is swept with a gate bias. This is a consequence of the pinning of the Fermi energy by the parabolic potential. Though the Fermi energy is near the top of the miniband, the generalized Kohn theorem surprisingly continues to hold. It is remarkable that we cannot observe a well defined Voigt geometry resonance, but that we see a well-defined plasma resonance.

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