

# Infrared absorption of holes in a parabolic quantum well

M. Sundaram<sup>a)</sup> and S. J. Allen, Jr.

Center for Quantized Electronic Structures, University of California, Santa Barbara, California 93106

M. R. Geller

Physics Department, University of Missouri, Columbia, Missouri 65211

P. F. Hopkins, K. L. Campman, and A. C. Gossard

Materials Dept., University of California, Santa Barbara, California 93106

(Received 25 April 1994; accepted for publication 13 July 1994)

We observe the infrared absorption of holes in a wide graded  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  parabolic quantum well to be at a single frequency, independent of the number of holes in the well. The resonant absorption frequency appears to be determined by the *light hole* mass, *not* the heavy hole mass.

The generalized Kohn theorem<sup>1,2</sup> states that electrons residing in a spatially parabolic potential well and in parabolic bands in  $k$  space absorb radiation at the bare harmonic oscillator frequency of the empty parabola irrespective of electron-electron interaction or the number of electrons in the well. This has been observed in a number of experiments on electron gases in parabolically graded  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  quantum wells,<sup>3-6</sup> as also on quantum wires<sup>7-9</sup> and dots<sup>7,10</sup> where the confining potential is, in most cases, approximately parabolic. The effect of deviations, both intentional and unintentional, from a perfectly parabolic shape of the potential well, has been investigated both theoretically<sup>11-13</sup> and experimentally.<sup>14-16</sup> With the exception of the case of a superlattice superimposed on the parabolic quantum well (where a mass-shifted generalized Kohn theorem response is observed),<sup>17</sup> the wells with deviations from perfect parabolicity display a violation of the theorem qualitatively and quantitatively consistent with a uniform radiation field now coupling not only to the center-of-mass oscillation of the electron gas, but also to its internal oscillations.

In this letter we present an experiment to test the theorem when the other condition, i.e., that the carriers reside in parabolic bands in  $k$  space is violated. A hole gas in a spatially parabolically graded  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  quantum well represents a good candidate for such a test. More importantly, the valence band is composite, i.e., composed of many branches. So, the experiment presented below tests the generalized Kohn theorem not just in nonparabolic bands, but also in composite bands. The Luttinger-Kohn Hamiltonian for a hole gas in an ideal parabolic quantum well *does not appear to allow* a clean division into two parts as for the above case, a part that depends only on the internal oscillations of the hole gas and another that depends only on the oscillation of its center of mass. Interaction with a uniform radiation field is therefore expected to yield a complex absorption spectrum. Yet, a remarkably simple result is obtained in the experiments below: a broad absorption whose peak frequency is independent of the number of holes in the well, and from whole value the carrier mass extracted is equal to that of the light hole in GaAs.

The sample was grown by conventional molecular beam epitaxy (MBE) on a (100) semi-insulating GaAs substrate

and consists of a 1000-Å-wide graded  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  alloy in which the Al mole fraction  $x$  is varied quadratically from 0.2 at the edges to 0.01 at the center (Fig. 1). The grading was accomplished using the digital alloy technique, i.e., the alloy is composed of a superlattice of period 20 Å, each period consisting of two layers, viz., GaAs and  $\text{Al}_{0.35}\text{Ga}_{0.65}\text{As}$ , and with the duty cycle of the latter varied quadratically. The period of the superlattice was chosen to be fine enough on the length scale  $(\hbar/m^*\omega)^{1/2}$  of variation of the low-lying envelope functions.<sup>18</sup> The well is sandwiched between two  $\text{Al}_{0.35}\text{Ga}_{0.65}\text{As}$  barriers; Be-doped regions in the barriers set back 105 Å from the well edges supply holes to the well. Ohmic contacts to the hole gas in the well were made by alloying In/Zn contacts to the sample surface; a Ti/Au gate was then evaporated onto the surface to provide a gate to tune the number of holes in the well as in a field effect transistor. The as-grown sample has a low temperature hole sheet density  $p_s = 4 \times 10^{11} \text{ cm}^{-2}$  with a mobility  $\mu = 23\,000 \text{ cm}^2/\text{V s}$ , as determined from Hall measurements. More details on the growth and characterization of this and other similar samples can be found elsewhere.<sup>18</sup>

The variation of the capacitance  $C$  between the front gate and the hole gas in the well as a function of the applied voltage  $V_g$  between the two ( $T = 4.2 \text{ K}$ ), is graphed in Fig. 2(a). The gate allows one to tune the hole density  $p_s = (1/e) \int C dV_g$  in the well from 0 (for  $V_g > V_T = 0.8 \text{ V}$ , the threshold voltage) to  $10^{12} \text{ cm}^{-2}$ . Using the depletion approximation expressions<sup>19</sup> for the 3D hole density  $p_0 = (2/e\epsilon) [d(1/C^2)/dV_g]^{-1}$  at the depth  $z = \epsilon/C$ , we extract the hole density distribution in the well [Fig. 2(b)].<sup>20</sup> A hole accumulation layer is observed at the top edge of the well at high forward bias; a wide hole gas at an approximately uniform density  $p_0 \sim 3 \times 10^{16} \text{ cm}^{-3}$  is seen to be dispersed across the rest of the well. Assuming the bandgap difference<sup>21</sup>  $\Delta E_g(x)$  between  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  and GaAs to be

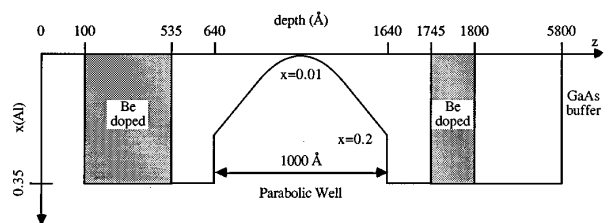


FIG. 1. Aluminum mole fraction versus depth showing parabolic quantum well. Be doping in the barriers supply holes to the well.

<sup>a)</sup>Present address: Jet Propulsion Laboratory, NASA, Mail Stop 302-231, 4800 Oak Grove Drive, Pasadena, CA 91109.

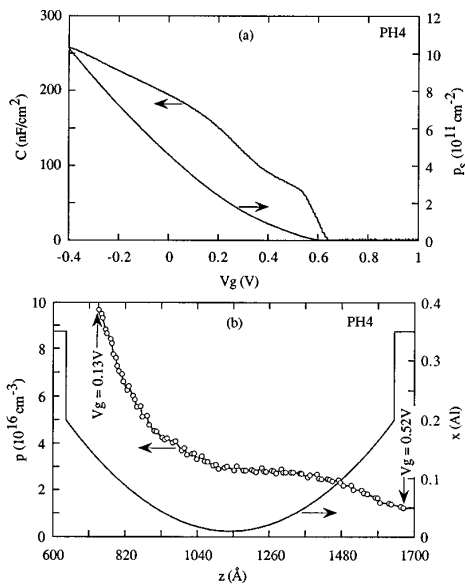


FIG. 2. (A) Capacitance vs gate voltage (applied between surface gate and ohmic contact to hole gas in parabolic well), and hole sheet density vs gate voltage for the sample ( $T=4.2$  K) in Fig. 1(b). Hole density distribution in the well calculated from (a) and overlaid on the design Al mole fraction profile of the parabolic well. The gate voltages between which the depletion edge is swept through the well are also indicated.

$\Delta E_g(x) = 1.425x - 0.9x^2 + 1.1x^3$ , and that 30% of this difference occurs in the valence band (i.e.,  $\Delta E_c/\Delta E_v = 70/30$ ), we calculate the depth of the above parabolic potential well  $\Delta = 73.1$  meV, with the 3D hole density corresponding to the well curvature  $p_0 = 4.2 \times 10^{16} \text{ cm}^{-3}$ , in approximate agreement with the observed value of  $p_0 \sim 3 \times 10^{16} \text{ cm}^{-3}$  (the difference may be due to a combination of growth parameter tolerances and uncertainty in the  $\Delta E_v$  value assumed for the calculation). The envelope functions (with zero in-plane momentum) of a single hole in a parabolic quantum well are those of a simple harmonic oscillator. Assuming<sup>22</sup> a heavy hole mass  $m_{hh} = 0.51m_e$  and a light hole mass  $m_{lh} = 0.082m_e$  (where  $m_e$  is the free electron mass) we arrive at harmonic oscillator (HO) energy ladder spacings of 2.99 meV (24.1  $\text{cm}^{-1}$ ) and 7.38 (59.5  $\text{cm}^{-1}$ ) meV for the heavy and light holes, respectively.

Optical measurements were performed with a conventional rapid scan BOMEM Fourier Transform Infrared (FTIR) spectrometer, with the radiation focused onto the edge of the sample placed in front of a composite bolometer (inset of Fig. 3). Both the sample and the bolometer were cooled to 4.2 K. A polarizer was placed between the focusing cone and the sample edge in some experiments. The transmittance is calculated as  $T(V_g)/T(V_g=1 \text{ V})$  with the transmission at the gate voltage  $V_g$  referenced to the transmission at  $V_g=1 \text{ V}$  at which gate voltage all the holes are depleted out of the well. The distance that the infrared beam travels through the sample in this slab geometry is approximately 4 mm. The spectra were measured with a resolution of 2  $\text{cm}^{-1}$ .

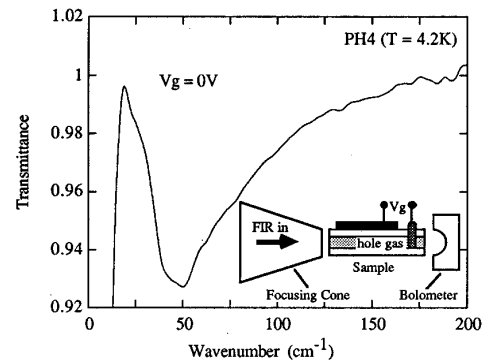


FIG. 3. Transmittance  $T(V_g=0 \text{ V})/T(V_g=1 \text{ V})$  at gate voltage  $V_g=0 \text{ V}$  shows absorption with a long high-energy tail, and a peak at  $\sim 50 \text{ cm}^{-1}$ . Inset shows measurements schematic (not to scale). Noise at low frequencies ( $< 20 \text{ cm}^{-1}$ ) is due to reduced transmission of the 12  $\mu\text{m}$  beamsplitter at this end.

The transmittance of unpolarized light at  $V_g=0 \text{ V}$  is shown in Fig. 3. It has a peak absorption of  $\sim 7\%$  at a resonance frequency of  $\sim 50 \text{ cm}^{-1}$ , and has an asymmetric line shape with a long tail extending to higher energy. This tail may be due to the nonparabolicity of the hole subband dispersion in  $k_{xy}$  space, caused by the mixing of the heavy and light holes away from the zone center, and has been observed in optical measurements on 2D hole gases.<sup>23,24</sup> On changing the gate voltage a series of transmittance spectra are obtained (Fig. 4) all of which show the same absorption line shape. The integrated absorption strength decreases with increasing positive gate voltage due to the decreasing number of holes, but the resonance frequency is held nearly fixed. One might have expected multiple features in the absorption especially at high negative gate bias where the hole density  $p_s$  is high enough to populate both heavy and light hole subbands in the well. One might have further expected these features to change with decreasing hole density in a manner consistent with the complete depopulation of first the light hole subbands followed by that of the heavy hole subbands. None of these features are observed. There is a single dominant peak at  $\omega_0 \sim 50 \text{ cm}^{-1}$  at all hole densities.

No absorption was measured (to within  $\pm 0.1\%$ ) when the light was polarized parallel to the  $xy$  plane in this slab geometry; nor was any absorption measured when the radiation was incident normally on the sample. Absorption was measured only when the electric field of the light was polarized parallel to the growth direction. This is in contrast to experiments on multiple square quantum wells where hole intersubband absorption at normal incidence has been observed, this selection rule being allowed by the mixing of the heavy and light hole bands away from the zone center.<sup>24,25</sup>

The resonance frequency  $\omega_0$  of the harmonic oscillator is by construction equal to the plasma frequency  $\omega_p = e(p_0/\epsilon m^*)^{1/2}$  of a 3D hole gas of uniform density  $p_0$ . Our optical measurement of  $\omega_0$  coupled with the electrical measurement of  $p_0$  allows us to extract a mass for the carriers in the hole plasma from experimentally measured values alone. We determine this mass to be  $m^* \sim 0.083m_e$ , which is very close to the light hole mass in GaAs. Should we attribute the observed resonance to the heavy hole, and extract

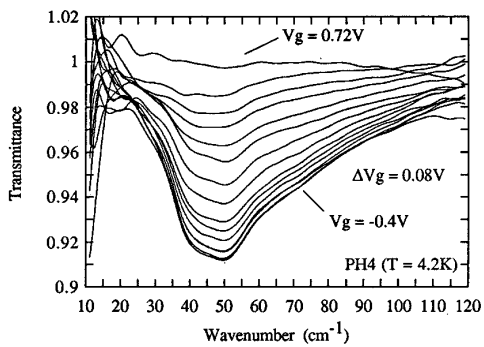


FIG. 4. Transmittance at a number of gate voltages from high forward gate bias to depletion bias shows decreasing absorption strength but with the peak absorption frequency held constant. Noise at low frequencies ( $<15 \text{ cm}^{-1}$ ) is due to reduced transmission of the  $25 \mu\text{m}$  beamsplitter at this end.

the heavy hole mass  $0.51m_e$  from it, we would have to assume the well curvature  $p_0$  to be  $\sim 6$  times higher, which is well outside the tolerances of MBE growth. Moreover, the value of the 3D hole density  $p_0$ , determined by experiment, is quite close to that calculated from the growth design. Hence, we unambiguously conclude the extracted mass to be the real mass of the carriers in the plasma.

A careful analysis of the in-plane dispersion of the heavy hole and light hole subbands of a hole gas in a parabolic quantum well, and its optical absorption, is clearly in order. Such an analysis might very well show the robustness of the generalized Kohn theorem under the particular constraints of nonparabolicity in the carrier dispersion relations considered here. Why do we observe a carrier mass that is so *light*? The answer could lie in strain effects.<sup>26,27</sup> Compressive (in-plane) strain causes the light hole subbands to move toward the top of the well while tensile strain causes them to move deeper into it. At a sufficiently high level of tensile strain, the light hole subband can move so far down into the well that it can become the lowest subband.<sup>26</sup> Notwithstanding the Al grading, it is possible that there is a little residual tensile strain at the parabolic well center ( $\text{Al}_{0.01}\text{Ga}_{0.99}\text{As}$ ) since it is grown on a thick and relaxed  $\text{Al}_{0.35}\text{Ga}_{0.65}\text{As}$  barrier layer of slightly larger lattice constant. For the empty parabolic well, we calculate<sup>28</sup> that the light hole HO ladder ( $\sim 7.4 \text{ meV}$  spacing) drops by  $\sim 2.4 \text{ meV}$  into the well with respect to the heavy hole HO ladder ( $\sim 3 \text{ meV}$  spacing). This places the lowest light hole level  $\sim 0.2 \text{ meV}$  below the lowest heavy hole level, making the lowest subband light hole-like. There are three heavy hole levels between the lowest two light hole levels. Remarkably, though, only the light hole resonance is observed in the experiment at all hole densities, up to densities where the heavy hole subbands are expected to be occupied. We have no explanations for this.

The experiment that suggest itself is the measurement of optical absorption in the sample as a function of externally applied stress which can be used as a tool to tune the heavy and light hole subbands.<sup>29</sup> It would then be interesting to see if the holes continue to absorb at a single dominant peak frequency.

In conclusion, we observe holes in a parabolic quantum well to absorb radiation at a constant frequency independent of the number of holes in the well. This resonance frequency corresponds to the plasma frequency of carriers having a

mass equal to the light hole mass for holes in a graded  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  parabolic quantum well grown on (100) GaAs substrate. The occurrence of the light hole mass might be due to residual tensile strain in the quantum well. The absorption at a single peak frequency at all gate biases (with the hole density changed from  $0\text{--}10^{12} \text{ cm}^{-2}$ ) begs explanation.

This work was supported in part by the National Science Foundation (NSF grant #DMR-91-20007) through QUEST, an NSF Science and Technology Center, at the University of California, Santa Barbara, by the Office of Naval Research (ONR grant #N000 15-92-J-1452), and by the Air Force Office of Scientific Research (grant #AFOSR-91-0214).

- <sup>1</sup>L. Brey, N. F. Johnson, and B. I. Halperin, *Phys. Rev. B* **40**, 10647 (1989).
- <sup>2</sup>For a recent review, see A. C. Gossard, M. Sundaram, and P. F. Hopkins, *Semiconductors and Semimetals* edited by R. K. Willardson and A. C. Beer (Academic, Boston, 1994), Vol. 42, p. 153, and references therein.
- <sup>3</sup>K. Karraï, H. D. Drew, M. W. Lee, and M. Shayegan, *Phys. Rev. B* **39**, 1426 (1989).
- <sup>4</sup>K. Karraï, X. Ying, H. D. Drew, and M. Shayegan, *Phys. Rev. B* **40**, 12020 (1989).
- <sup>5</sup>A. Wixforth, M. Sundaram, J. H. English, and A. C. Gossard, in *Proceedings of the 20th International Conference on the Physics of Semiconductors*, edited by E. M. Anastassakis and J. D. Joannopoulos (World Scientific, Singapore, 1990), Vol. 2, p. 1705.
- <sup>6</sup>A. Wixforth, M. Sundaram, K. Ensslin, J. H. English, and A. C. Gossard, *Phys. Rev. B* **43**, 10 000 (1991).
- <sup>7</sup>For a recent review, see W. Hansen, U. Merkt, and J. P. Kotthaus, *Semiconductors and Semimetals*, edited by R. K. Willardson, A. C. Beer, and E. R. Weber (Academic, San Diego, 1992), Vol. 35, p. 279, and references therein.
- <sup>8</sup>W. Hansen, M. Horst, J. P. Kotthaus, U. Merkt, Ch. Sikorski, and K. Ploog, *Phys. Rev. Lett.* **58**, 2586 (1987).
- <sup>9</sup>T. Demel, D. Heitmann, P. Grambow, and K. Ploog, *Phys. Rev. Lett.* **64**, 788 (1990).
- <sup>10</sup>Ch. Sikorski and U. Merkt, *Phys. Rev. Lett.* **62**, 2164 (1989).
- <sup>11</sup>L. Brey, J. Dempsey, N. F. Johnson, and B. I. Halperin, *Phys. Rev. B* **42**, 1240 (1990).
- <sup>12</sup>L. Brey, N. F. Johnson, and J. Dempsey, *Phys. Rev. B* **42**, 2886 (1990).
- <sup>13</sup>M. P. Stopa and S. Das Sarma, *Phys. Rev. B* **45**, 8526 (1992).
- <sup>14</sup>E. L. Yuh, E. G. Gwinn, P. R. Pinsukanjana, W. L. Schaich, M. Sundaram, P. F. Hopkins, and A. C. Gossard, *Phys. Rev. Lett.* **71**, 2126 (1993).
- <sup>15</sup>A. Wixforth, M. Sundaram, K. Ensslin, J. H. English, and A. C. Gossard, *Surf. Sci.* **267**, 523 (1992).
- <sup>16</sup>X. Ying, K. Karraï, H. D. Drew, M. Santos, and M. Shayegan, *Phys. Rev. B* **46**, 1823 (1992).
- <sup>17</sup>M. Sundaram, M. R. Geller, K. L. Campman, S. J. Allen, Jr., and A. C. Gossard (unpublished).
- <sup>18</sup>P. F. Hopkins, K. L. Campman, and A. C. Gossard, *J. Cryst. Growth* **127**, 798 (1993).
- <sup>19</sup>H. Kroemer, W. Y. Chien, J. S. Harris, Jr., and D. D. Edwall, *Appl. Phys. Lett.* **36**, 295 (1980).
- <sup>20</sup>M. Sundaram, S. J. Allen, Jr., and A. C. Gossard, *J. Appl. Phys.* **76**, 1003 (1994).
- <sup>21</sup>R. C. Miller, D. A. Kleinman, and A. C. Gossard, *Phys. Rev. B* **29**, 7085 (1984).
- <sup>22</sup>Data in Science and Technology. *Semiconductors: Group IV Elements and III-V Compounds*, edited by O. Madelung (Springer, Berlin, 1991), p. 103.
- <sup>23</sup>A. D. Wieck, E. Batke, D. Heitmann, and J. P. Kotthaus, *Phys. Rev. B* **30**, 4653 (1984).
- <sup>24</sup>B. F. Levine, S. D. Gunapala, J. M. Kuo, S. S. Pei, and S. Hui, *Appl. Phys. Lett.* **59**, 1864 (1991), and references therein.
- <sup>25</sup>S. D. Gunapala, B. F. Levine, D. Ritter, R. Hamm, and M. B. Panish, *J. Appl. Phys.* **71**, 2458 (1992).
- <sup>26</sup>S. W. Corzine and L. A. Coldren, *Appl. Phys. Lett.* **59**, 588 (1991).
- <sup>27</sup>S. W. Corzine, R. H. Yan, and L. A. Coldren, *Appl. Phys. Lett.* **57**, 2835 (1990).
- <sup>28</sup>J. Singh, *Physics of Semiconductors and their Heterostructures* (McGraw-Hill, New York, 1993), Chap. 7.
- <sup>29</sup>A. Pinczuk, D. Heiman, R. Sooryakumar, A. C. Gossard, and W. Wiegmann, *Surf. Sci.* **170**, 573 (1986).