Determination of subband spacing in inversion layers on *p*-type InAs

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Recently, Kunze investigated electric subbands in the inversion layer on degenerate *p*-type InAs by means of Zener tunneling. He inferred energy separations between low-lying subbands in a sample with bulk acceptor concentration in the 10^{17} cm^{-3} range. However, prior to this experiment, Übensee, Paasch, and Gobsch had calculated separations which differ significantly from Kunze's values. Experimental evidence from intersubband spectroscopy is presented here which is in agreement with the predictions of Übensee, Paasch, and Gobsch, as well as with the results of our own self-consistent calculation.

Degenerate InAs has proven to be a rich system on which to study the details of the two-dimensional electron gas (2DEG), particularly because of the strong influence of band nonparabolicity on the spectrum of electronic states. Recent experimental and theoretical work has focused on the spectrum, the spatial extent, and the amplitude of the bound states in both accumulation layers on *n*-type InAs (Refs. 1–3) and in inversion layers on *p*-type InAs.[4–6] In particular, we note that the subband populations for the *n*-channel inversion layer have been well established experimentally by Yamaguchi,[6] and corroborated by the theoretical calculation of Übensee, Paasch, and Gobsch.[5] However, the energy spacings of the subbands in this case had not been determined experimentally.

In a recent paper, Kunze[4] interpreted his Zener tunneling measurements to yield intersubband spacings. Because of the substantial disagreements between these spacings and the predictions of Übensee, Paasch, and Gobsch, we were motivated to apply a more traditional technique to determine the subband spacings in *n* inversion, namely, intersubband spectroscopy. This technique has proven to be a powerful probe of the subband structure for the 2DEG on several materials such as Si and GaAs. In narrow-band-gap materials, where intersubband resonance can be observed without a depolarization shift, it is extremely useful, as has been shown for accumulation layers on *n*-type InAs.[1,3] In this Brief Report we present our experimental data as well as the results of applying a self-consistent calculation[2] to the inversion layers on *p*-type InAs to compare to the spacings as calculated by Übensee, Paasch, and Gobsch using their "modified local-density-approximation" method.

The samples used in our experiments were prepared on commercially available *p*-type InAs wafers. The nominal acceptor concentration for the particular sample for which data are reported here was 8.2×10^{16} cm^{-3}. Details of the sample preparation are identical to that described in Ref. 3. As indicated in the inset to Fig. 1, infrared radiation from a CO_2 laser was reflected off the sample at an angle of 45°. The gate bias was modulated so that the reflectivity derivative dR/dN_S was monitored using a Ge bolometer. This modulated reflectivity was plotted as a function of induced electron density N_S, determined from the applied gate voltage together with the sample capacitance. Figure 1 shows a characteristic line shape for laser photon energy $\hbar\omega=136$ meV. The dominant part of the line shape is identified as the depolarization-shifted resonance due to transitions from the ground subband to the first excited subband ($\widetilde{0\text{-}1}$). The line shape differs from the usual (derivative) Lorentzian due to strong mixing of signals reflected from both the inversion layer and the interface between the de-

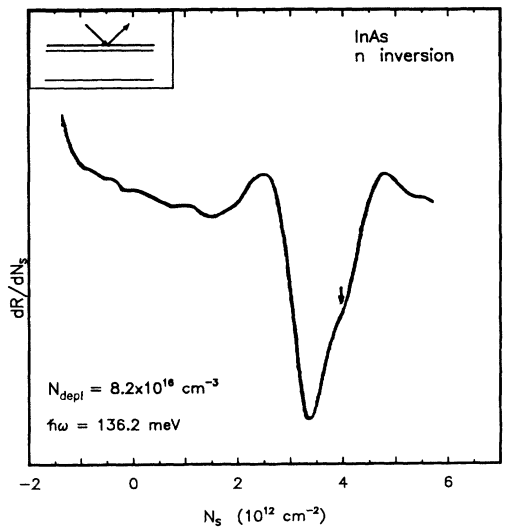

FIG. 1. Reflectance derivative, dR/dN_S, vs N_S at fixed laser frequency. The arrow indictates the position of the bare 0-1 resonance. The inset shows schematically the reflection geometry used in the experiment. The radiation is unpolarized.

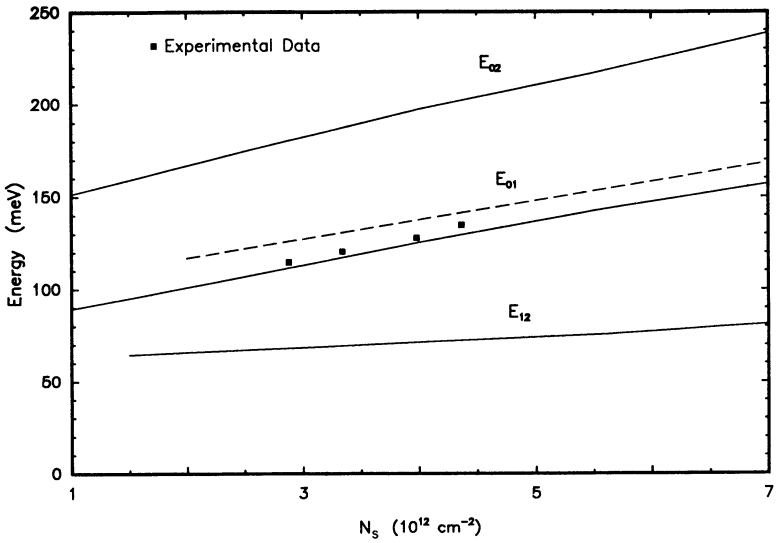

FIG. 2. Intersubband energy spacings vs N_S. The three solid curves are taken from our self-consistent calculation and are labeled by transition as described in the text. The dashed curve is the result of Übensee, Paasch, and Gobsch (Ref. 5) for the 0-1 spacing.

pletion layer and the bulk. The arrow indicates where we have marked the bare 0-1 resonance, unshifted by depolarization screening. The appearance of both shifted and unshifted resonances is characteristic of intersubband resonance in narrow-band-gap materials in the presence of both *s*- and *p*-polarized incident radiation.[7] It is the ability to observe the bare resonances, coupled to the in-plane radiation fields through the nonparabolicity, which makes intersubband resonance especially useful in narrow-band-gap semiconductors.

Figure 2 shows the calculated subband energy differences between the ground state and first-excited state (E_{01}), the ground state and second-excited state (E_{02}), and between the first- and second-excited states (E_{12}), all as functions of N_S. Our calculation was based on the fully self-consistent, four-band model as described in Ref. 2. The experimental points in Fig. 2 are the intersubband transition energies as determined from the lineshape data for four different laser lines. The agreement between the E_{01} from our calculation, as well as from that of Übensee, Paasch, and Gobsch and the experimental data is quite good. It is evident that the subband energy differences in this N_S range are between 110 and 135 meV. Kunze[4] extracts an E_{01} value of 184 meV from his tunneling data for the same range of N_S values. This range can be determined from the observed Shubnikov–de Haas subband thresholds,[6] which show that the first excited subband is occupied above 2×10^{12} cm^{-2} and suggest that the second excited subband is occupied above 6×10^{12} cm^{-2} (in agreement with both calculations). At zero bias, Kunze's data indicate that the Fermi level is located approximately halfway between the first- and second-excited subband edges. We therefore find that the N_S value corresponding to Kunze's measurements should lie in the range 3×10^{2}–5×10^{12} cm^{-2}. Our self-consistent calculation indicates that Kunze's slightly higher depletion charge density, 2.3×10^{17} cm^{-3}, gives rise to a 0-1 spacing only ~3% higher than that shown in Fig. 2. Kunze's E_{01} value is therefore in serious disagreement with our intersubband measurements as well as with both self-consistent calculations. The influence of the applied bias in the tunneling experiment on the surface potential, as discussed by Tsui,[8] is a likely source of the discrepancy. This is also suggested by the near agreement between Kunze's E_{12} value (~60 meV) and the prediction of our calculation in Fig. 2.

The subband occupation densities N_i, obtained experimentally by Yamaguchi,[6] are in excellent agreement with our calculation as well as with the calculation of Übensee, Paasch, and Gobsch (see Fig. 1 of Ref. 5). The agreement of the calculations with both the Shubnikov–de Haas results as well as with the measured intersubband resonance reported here lends great credence to the self-consistent calculations.

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[1]H. Reisinger, H. Schaber, and R. E. Doezema, Phys. Rev. B **24**, 5690 (1981); H. Reisinger, Doctoral dissertation, Technische Universität München, 1983.

[2]An-zhen Zhang, J. A. Slinkman, and R. E. Doezema, Phys. Rev. B **44**, 10752 (1991).

[3]Y. Zhang, A. Zhang, J. A. Slinkman, and R. E. Doezema, Phys. Rev. B **44**, 10749 (1991).

[4]U. Kunze, Phys. Rev. B **41**, 1707 (1990).

[5]H. Übensee, G. Paasch, and G. Gobsch, Solid State Commun. **62**, 699 (1987).

[6]E. Yamaguchi, Phys. Rev. B **32**, 5280 (1985).

[7]K. Wiesinger, H. Reisinger, and F. Koch, Surf. Sci. **113**, 102 (1982).

[8]D. C. Tsui, Phys. Rev. B **8**, 2657 (1973).