

## Resonance Spectroscopy of Electronic Levels in a Surface Accumulation Layer

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Resonance transitions are observed between electronic levels in an accumulation layer on  $n$ -type (100)Si. Signals are studied at the 220-, 171-, and 118- $\mu\text{m}$  lines of a water-vapor ( $\text{H}_2\text{O}$ ,  $\text{D}_2\text{O}$ ) molecular laser. Strong transitions from the lowest two-dimensional sub-band to the next higher band are observed. For 118- $\mu\text{m}$  radiation the resonance occurs at about  $0.6 \times 10^{12}$  electrons/ $\text{cm}^2$ .

An electric field applied normal to the surface of a semiconductor results in a space-charge layer in the surface region. For an  $n$ -type Si sample, and field directed into the sample surface, one finds an accumulation layer of electrons. The electronic levels in the space-charge region are quantized with respect to their motion normal to the surface.

Several years ago Duke<sup>1</sup> explicitly treated the case of electrons accumulated on a (100) surface of Si and suggested that resonance-absorption experiments at far-infrared frequencies could provide a direct and sensitive measurement of the localized electronic states. Duke<sup>1</sup> proposed a self-consistent model of the space-charge potential and applied it to evaluate binding energies and electronic wave functions. The more recent work of Baraff and Appelbaum<sup>2</sup> has addressed itself to the same problem. We report here the very first observation of direct infrared absorption due to transitions between the quantized, electric-field-induced states at a semiconductor surface.

Our experiments make use of a far-infrared molecular laser ( $\text{H}_2\text{O}$ ,  $\text{D}_2\text{O}$ ) operating at the 220-, 171-, and 118- $\mu\text{m}$  lines. As in Fig. 1, the laser beam is guided into the cryostat in polished-brass light pipes. The gradual taper channels the radiation into the space between the two parallel copper plates which form a transmission line operating predominantly in the TEM mode.<sup>3</sup> For this mode of propagation the high-frequency electric field is polarized normal to the copper plates.

The sample<sup>4</sup> is a very thin,  $6 \times 6 \text{ mm}^2$  slab of phosphorus-doped,  $n$ -type Si with resistivity of approximately  $10 \Omega \text{ cm}$ . The orientation is (100). A 2100- $\text{\AA}$ -thick layer of  $\text{SiO}_2$  has been thermally grown onto the surface, and several hundred angstroms of Al have been evaporated onto each side of the sample. The sample is placed between the two copper plates of the transmission line.

In the experiments the gate voltage  $V_g$  is swept

from 0 to a maximum of +30 V. We modulate  $V_g$  with an amplitude of less than 1 V peak to peak and at a frequency of about 1 Hz. Our experience with capacitance measurements<sup>5</sup> in similar samples has shown that the majority-carrier conductivity is adequate to charge and discharge the accumulation layer across the Si at 4.2°K. We use a Ge bolometer to detect the infrared radiation. The detector gives a signal coherent with the reference and proportional to the voltage derivative of power absorbed ( $dP/dV_g$ ) in the sample.

Because of the mobile charge accumulated in the surface region the electric field inside the Si is attenuated with distance into the sample. The self-consistent potential according to Duke<sup>1</sup> decreases exponentially with a decay length and strength adjusted to give just the right amount of charge  $Q_s$  and the correct value of Fermi energy  $E_F$ . Figure 2 shows schematically the potential well in the space-charge region, together with a number of possible energy levels labeled  $n=0, 1, 2$ , etc. Each of the levels corresponds to a two-dimensional, parabolic sub-band of states

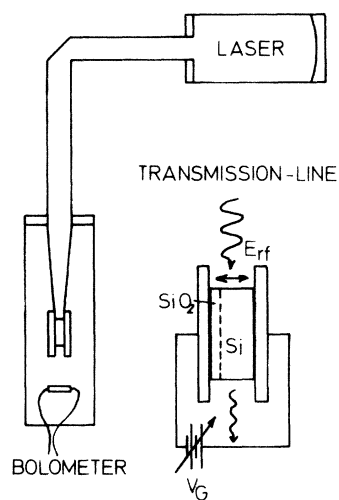


FIG. 1. Experimental arrangement.

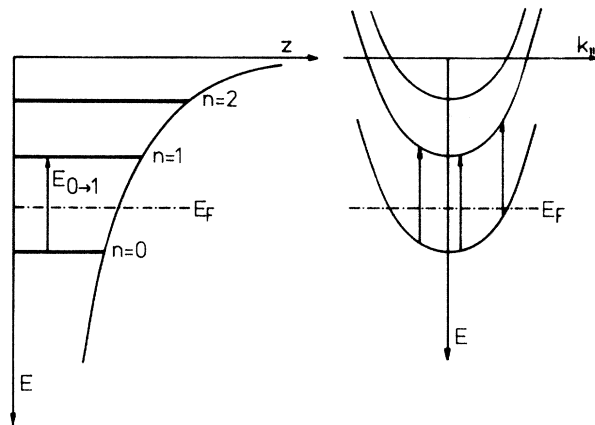


FIG. 2. Surface potential well and energy levels for an accumulation layer on *n*-type (100)Si. For a surface charge density of  $10^{12}$  electrons/cm<sup>2</sup> the energy-level separations are on the order of 10 meV and only the first sub-band is occupied. Possible transitions between the parabolic two-dimensional sub-bands are indicated.

with energies  $E_n(k_{\parallel}) = E_n + (\hbar^2/2m_{\parallel})k_{\parallel}^2$ . Here  $k_{\parallel}$  and  $m_{\parallel}$  are the electron wave vector and effective mass for motion parallel to the surface. The sub-bands are also sketched in Fig. 2 and possible transitions between filled  $n=0$  states and empty  $n=1$  levels are indicated. For a value of Fermi energy  $E_F$  between  $E_0$  and  $E_1$  all the occupied electron states contribute to the resonance.

For our samples the donor ionization energy is 44 meV and the Fermi level at low temperature, assuming the material to be partially compensated, would be close to this value. Duke<sup>1</sup> has calculated the energy levels for  $Q_s = 10^{12}$  electrons/cm<sup>2</sup> and for the specific case of a Si(100) surface. The calculation (Fig. 5 of Ref. 1) is for the electrons with heavy mass ( $m_{\perp} = 0.98m_0$ ) normal to the surface. Duke's calculated curves do not quite extend to sufficiently high energies to cover our case of  $E_F = 44$  meV. It is necessary to extrapolate somewhat beyond the calculation to find that the separation  $E_1 - E_0$  is something like 15 meV. For our highest frequency the photon energy is  $\hbar\omega = 10.45$  meV. We would expect to observe the  $0 \rightarrow 1$  transition at a  $Q_s$  value somewhat below  $10^{12}$  electrons/cm<sup>2</sup>. According to Duke only the lowest sub-band is occupied to an energy of 6.4 meV above the bottom of the band.

Figure 3 shows data of the far-infrared absorption ( $dP/dV_g$ ) as a function of gate voltage  $V_g$ . If we neglect the presence of localized trap states

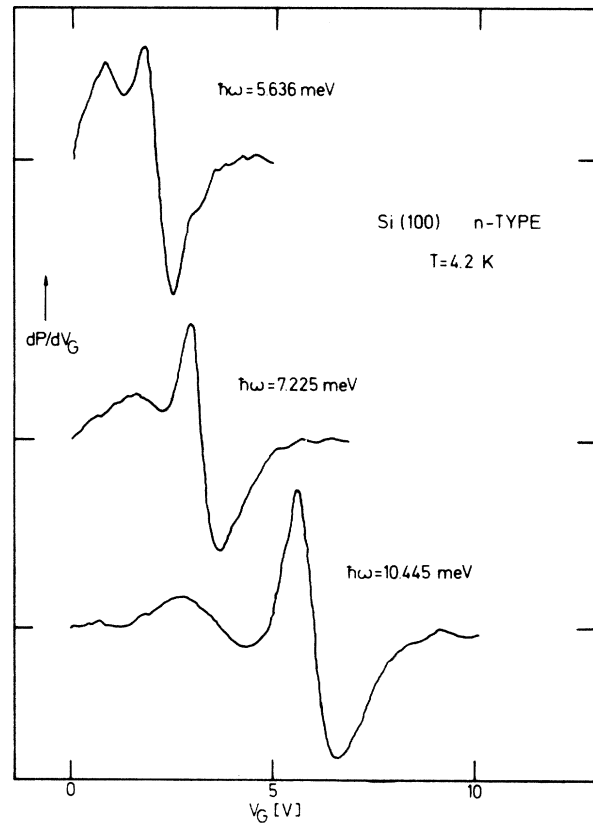


FIG. 3. Absorption derivative  $dP/dV_g$  traces for three frequencies.

in the oxide or at the Si-SiO<sub>2</sub> interface, then a gate voltage of approximately 10 V in Fig. 3 translates into a surface-charge density of  $10^{12}$  electrons/cm<sup>2</sup>. The resonance for  $\hbar\omega = 10.45$  meV occurs at 5.7 V. With the above estimate of energies in mind, it is evident that we must interpret this as a  $0 \rightarrow 1$  transition between the occupied first sub-band and the higher-lying, unoccupied, second sub-band. Other transitions such as  $0 \rightarrow 2$ ,  $0 \rightarrow 3$ , etc. should be observed at lower gate voltages. Some structure indeed does appear and is likely due to the higher transitions. We cannot at present identify them in detail, but it is clear that the higher-order transitions are not as strong as the  $0 \rightarrow 1$  resonance. A possible reason for this is that the matrix element coupling the  $n=0$  state to the more-extended higher states decreases as the spatial overlap of the corresponding wave functions decreases. We have not seen transitions from the second sub-band to higher levels, such as  $1 \rightarrow 2$  transition. This is because the second sub-band is not occupied until substantially higher voltages are

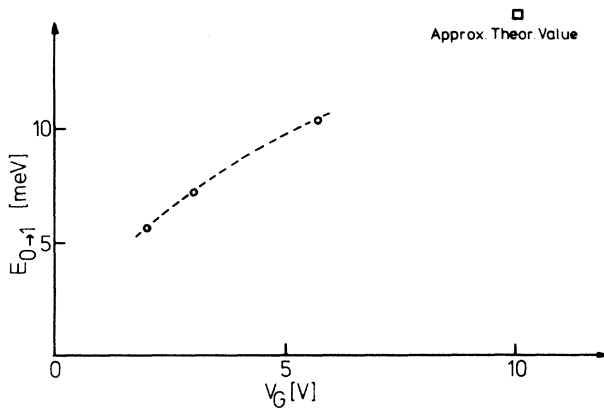


FIG. 4. Plot of measured energy-level separation  $E_{0 \rightarrow 1}$  as a function of gate voltage  $V_g$ . The theoretical point (Ref. 1) for  $Q_s = 10^{12}$  electrons/cm<sup>2</sup> has been entered at  $V_g = 10$  V for our samples.

reached. For these the spacing would then be too large for the applied frequency.

Figure 3 also contains data on the  $0 \rightarrow 1$  transition at photon energies of 7.23 and 5.64 meV, all for the same sample. The peak is found to shift to 3.0 V and then to 2.1 V. In each case we take the zero crossing of  $dP/dV_g$  as the resonance voltage. Figure 4 summarizes our results for  $E_{0 \rightarrow 1}$  as a function of  $Q_s$  for one particular sample. Also shown is the value 15 meV which we extrapolated from the calculations for  $Q_s = 10^{12}$  electrons/cm<sup>2</sup>. Evidently  $E_{0 \rightarrow 1}$  is not simply proportional to  $V_g$ . For the complex, self-consistent potential in the accumulation layer no simple relation is to be expected. Moreover,  $E_{0 \rightarrow 1}$  is not a unique function of  $V_g$  because, as is well known, at zero gate voltage the energy bands are not necessarily flat. Charged, immobile, trap states in the oxide or at the interface are expected to give some band bending even in the absence of applied field. These expectations are borne out in work with different samples. Some small variations in the gate-voltage value at resonance is found from sample to sample. For the samples tested so far the variation has been  $\pm 0.3$  V for the 118- $\mu$ m resonance at 5.7 V.

In principle one obtains the electron lifetime  $\tau$  from the width of the resonance curve, provided the line shape is adequately known. The exact form of the resonance line remains to be determined, but a first guess is that it is a Lorentzian with some distortion because of the fact that the lines are relatively wide. As one sweeps through the line both the number of occupied states and

the matrix elements are changing. Using Fig. 4 we can translate a voltage width  $\Delta E$  into a lifetime,  $\Delta E \sim \hbar/\tau$ . For the  $\hbar\omega = 7.23$  meV resonance the observed voltage width of 1.4 V gives a lifetime of  $\tau \sim 0.3 \times 10^{-12}$  sec. From cyclotron-resonance studies<sup>7</sup> we find  $\tau \sim 1 \times 10^{-12}$  sec for inversion-layer electrons. Another cause of linewidth could be spatial fluctuations of the potential.<sup>8</sup>

It is of interest to compare the present experiments with the earlier work of Wheeler and Ralston,<sup>9</sup> where the claim was made to have seen a photoconductance effect in an inversion layer on (100)Si. In this cross-modulation type of experiment the  $0 \rightarrow 1$  transition was not seen at all. Subsidiary peaks were interpreted as due to  $0 \rightarrow 2$ ,  $3, 4$ , etc. transitions. With some modifications of our laser apparatus, we hope soon to study inversion layers on Si using the present transmission-line technique and measuring the direct absorption. We have reason to believe that the accumulation-layer resonance is an inherently stronger effect than the inversion-layer case, because the typical binding length of the accumulation-layer electron is about 10 times bigger at similar gate voltages. As a consequence the dipole matrix element coupling the two states is expected to be correspondingly greater.

Our experiment is in principle closely related to the work of Grimes and Brown,<sup>10</sup> where electrically bound electrons on the surface of liquid helium are observed in microwave resonance. The tunneling experiments of Tsui<sup>11</sup> are also capable of measuring energy levels in an accumulation layer. The microwave experiments on resonance spectroscopy of magnetically bound surface electrons<sup>12</sup> are a magnetic analog of the present work.

In concluding we like to acknowledge many stimulating discussions with our colleagues G. Abstreiter and J. P. Kotthaus. Many thanks go to E. Seifert for the very expert construction of laser parts and the transmission-line assembly.

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<sup>1</sup>C. B. Duke, Phys. Rev. **159**, 632 (1967).

<sup>2</sup>G. Baraff and J. Appelbaum, Phys. Rev. B **5**, 475 (1972).

<sup>3</sup>The strip transmission line has been used extensively in our previous far-infrared laser experiments. See for example, U. Strom, A. Kamgar, and J. F. Koch, Phys. Rev. B **7**, 2435 (1973).

<sup>4</sup>The sample was kindly supplied to us by the Semi-

conductor Research Division of Siemens AG, München, West Germany.

<sup>5</sup>P. Kneschaurek, Diplom thesis, Technischen Universität München, 1974 (unpublished).

<sup>6</sup>A better value is  $m_{\perp} = 0.916m_0$  [J. C. Hensel, H. Hasegawa, and M. Nakayama, *Phys. Rev.* **138**, A225 (1965)]. This, however, would not change the energy levels significantly.

<sup>7</sup>G. Abstreiter, P. Kneschaurek, J. P. Kotthaus, and

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<sup>8</sup>T. H. Ning and C. T. Sah, *Phys. Rev. B* **9**, 527 (1974).

<sup>9</sup>R. G. Wheeler and R. W. Ralston, *Phys. Rev. Lett.* **27**, 925 (1971).

<sup>10</sup>C. C. Grimes and T. R. Brown, *Phys. Rev. Lett.* **32**, 280 (1974).

<sup>11</sup>D. C. Tsui, *Phys. Rev. B* **8**, 2657 (1973).

<sup>12</sup>See, for example, R. E. Doezema and J. F. Koch, *Phys. Rev. B* **5**, 3866 (1973).

## Ultrasonic Attenuation near the Ferromagnetic-Spiral Transition in Dysprosium and Terbium Metals

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Ultrasonic attenuation near the ferromagnetic-spiral transition of Dy and Tb is described on the basis of magnetoelastically driven domain-wall resonance. Good agreement with the measured attenuation coefficient is obtained on the basis of a simple model, and an apparent discrepancy between zero-field observations is discussed.

The attenuation of ultrasonic waves, propagating along the  $c$  axis of hexagonally close-packed Dy and Tb metals, has been carefully measured.<sup>1,2</sup> Although a very large, rather symmetric peak near the Curie temperature  $T_C$  is observed for the attenuation coefficient of longitudinal sound, no absorption is recorded for transverse waves. The longitudinal absorption in Tb was observed in zero magnetic field; and although the magnetic and crystallographic structures of Dy and Tb are quite similar, no zero-field absorption in Dy was observed. Rather, a magnetic field of 2.8 kOe along the easy magnetic axis was needed to produce measurable absorption. When the field was increased to 5.5 kOe, a well-defined symmetric peak centered at  $T_C$  was observed; further increase to 9.2 kOe caused a dramatic sixfold increase in the height of this peak.

At temperatures below the first-order magnetic transition at  $T_C$ , the moments are ferromagnetically aligned and confined to the basal plane by large axial anisotropy. Above  $T_C$  the moments are again ferromagnetically aligned in planes perpendicular to the  $c$  axis, but the direction of alignment rotates from plane to plane, giving rise to the planar spiral structure. Although the magnetization  $\vec{M}(\vec{H}, T)$  drops abruptly as the crystal is warmed through  $T_C$ , the change is not discontinuous.<sup>3,4</sup> For example, in Dy the transition occurs within a 10–20°K range for applied fields up to 8 kOe; in Tb, for an applied field

of 1 kOe, the transition occurs in a 15°K range. In nonellipsoidal samples, extensive demagnetizing fields are much weaker near the center of the sample than near the surfaces.<sup>5</sup> This and other more complicated local straining effects create large inhomogeneities in the internal field near  $T_C$ , so that some regions of the crystal transform before others.

In our discussion we take  $T_C$  to be experimentally defined as that temperature at which the magnetization curve takes on its greatest slope. When the crystal begins to transform, very near  $T_C$ , a complicated mixed phase develops in which both ferromagnetic and spiral-antiferromagnetic domains coexist, separated from one another by Bloch walls, lying primarily in planes perpendicular to the  $c$  axis. These Bloch walls are pinned to inclusions and other crystal imperfections which present local potential barriers to wall movement. As the crystal is warmed through  $T_C$ , the more weakly pinned walls move and merge with other more strongly pinned walls to create more antiferromagnetic structure. Away from  $T_C$  only a small number of Bloch walls remain near isolated regions of abnormally high internal-field inhomogeneity. The most highly mixed phase is at  $T_C$ , where the Bloch walls are most numerous and mobile: Not only do we find the strongly pinned walls that still exist away from  $T_C$ , but also many weakly pinned walls that give rise to the large susceptibility at  $T_C$ .