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ELECTROABSORPTION SPECTRUM IN SILICON

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In examining the absorption spectral response of silicon in the presence of an electric field we have seen some hitherto unreported structure. Our differential technique yields measurements of the change $\Delta\alpha$ in the absorption coefficient α, arising from the application of an electric field F to the specimen. Figure 1 shows curves of $\Delta\alpha$ vs photon energy for two different values of applied field. We have been exploring the 0.9- to 1.5-micron region of the spectrum where the absorption edge due to electron interband transitions begins. The experiments were performed at room temperature.

The specimens, made of 400- to 600-ohm-cm p-type silicon, were single-crystal-hyperpure 10-mil wafers lapped in the (111) plane, obtained from Dow Corning Corporation. These wafers were optically polished on both sides to a thickness of 4-5 mils and etched in CP-4 to a final thickness of 1-3 mils. After a thorough wash in de-ionized water, they were dried and an epoxy edge protection was applied. A transparent gold layer was evaporated on one side and a transparent aluminum layer on the opposite side of the wafer. The field was applied between these two transparent electrodes. This sample preparation technique, except for the transparent aluminum electrode, follows closely that described[1,2] for constructing surface-barrier nuclear particle detectors. We have used this construction in order to produce high electric fields in the samples without driving high currents through them. This is achieved by applying the field in the reverse bias direction. Using samples at room temperature without a surface barrier or with forward-bias fields, the shift of the absorption edge due to large current ohmic heating masks the high-field effects. With 50 to 100 volts across these samples, they are fully depleted. Thus we operate in a range where the field strength through the specimen is given by the applied voltage divided by the sample thickness.

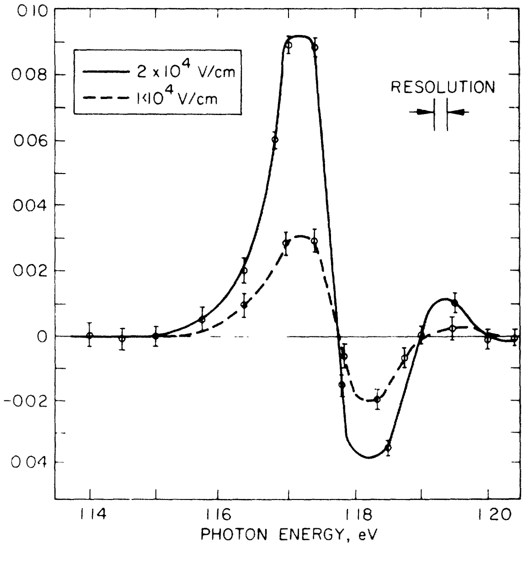

FIG. 1. Electric-field-induced absorption difference vs photon energy.

A differential technique was used to measure the small change in absorption which occurs upon application of an electric field (see Fig. 2). Steady unchopped light from a Bausch and Lomb high-intensity grating monochromator was focused on the Si sample located a few millimeters away from the exit slit. Square-wave voltage pulses were applied to the sample with a frequency of 50 cps and a duty cycle of 10%. The field variations produced by these pulses changed the ab-

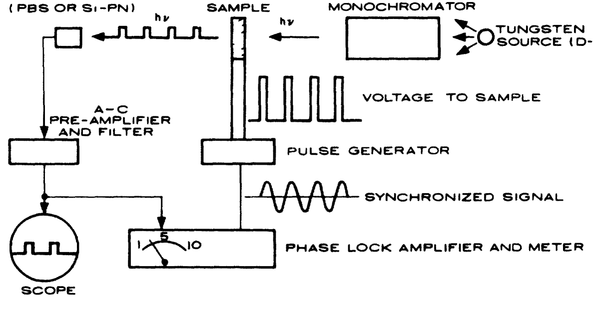

FIG. 2. Differential measurement system.

sorption coefficient of the specimen. The light transmitted by the Si was detected with a PbS cell, located a few millimeters behind the silicon. The detector output voltage varied with the change in transmitted intensity produced by the 50-cycle field variations. This output was fed to an ac preamplifier and then to a lock-in amplifier which was synchronized to the 50-cycle voltage pulses. Readings were taken from the meter on the lock-in amplifier and also from a recorder attached to the output. An oscilloscope monitored the amplified detector output wave form for viewing under high signal conditions. The differential absorption coefficient due to the field is obtained from the relationship $\Delta\alpha(F) = \Delta T/Td$ where ΔT is the differential transmission signal, T is the total transmission in zero field, and d is the sample thickness.

Figure 1 shows the variation of the differential absorption coefficient with photon energy for two fixed values of applied field. The structure appears as three "lines", two positive ones and one negative one. It is significant that the energy positions of maxima and minima do not change perceptibly with field strength. The relative magnitude of the differential absorption coefficient as a function of the applied electric field is presented in Fig. 3. The solid curve is measured at the peak of the large positive line. The dashed one is measured at the peak of the negative dip.

In 1958, both Franz[3] and Keldysh[4] independently predicted shifts of the absorption edge toward the red when strong electric fields are applied to an insulating or semiconducting crystal. Since that time several investigators[5-8] have reported qualitative or semiquantitative experimental verification of the predictions. Recently, Callaway,[9,10] in an extensive theoretical treatment, has predicted a field-induced oscillatory behavior in the absorption at energies above the band edge. This results indirectly from the discrete Wannier "Stark" levels[11] produced in the band system by the external field.

Unfortunately, there is no calculation extant on the effects of an electric field on an indirect absorption edge. The theoretical calculations mentioned above are for direct-absorption materials. As a result, our data are not amenable to immediate comparison with any theory presently available. This is because the absorption edge of silicon is due to indirect (phonon-assisted) transitions[12] rather than direct ones.

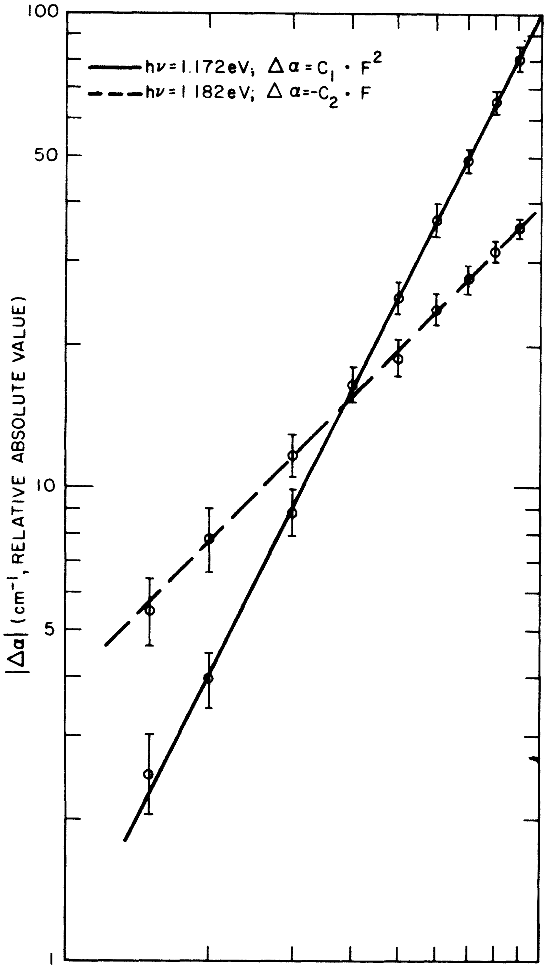

FIG. 3. Variation of line intensities with field strength.

We have considered some possible interpretations of our data. The likelihood that we are seeing some direct manifestations of the Wannier "Stark" ladder seems remote because (1) the "lines" are on the low-energy side of the absorption edge and not on the high-energy side, (2) their positions do not change with field strength, and (3) they are quite sharp—widths less than kT. Interpretations of the data as a Stark splitting of the levels of an exciton or exciton-complex also appear implausible because the "line" spacings, which would correspond to the splittings, are about 0.02 eV. This energy is greater than the entire exciton binding energy and, hence, is too large for a Stark splitting.

The observed "difference lines" fall in one of the phonon-assisted absorption threshold regions —around 1.17 eV—reported by Macfarlane et al.[12] Taking account of this and the foregoing, we are now testing the following interpretation which relates these facts.

In the presence of the electric fields applied, the electrons can be shown to attain velocities approaching that of sound. Such motion gives rise to a rather large Doppler shift in the phonon spectrum as seen by the speeding electrons. Frequency shifts sufficient to account for the 0.01 eV "line" spacings are easily obtained for electrons moving at 0.05 to 0.3 of the velocity of sound. And this hypothesis yields several other qualitative features of the experimentally observed results. Further investigations, both theoretical and experimental, are in progress to test the Doppler-shift conjecture quantitatively.

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RADIO-FREQUENCY EFFECTS IN SUPERCONDUCTING THIN FILM BRIDGES

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Parks and Mochel[1] have observed structure in the resistive behavior of a very fine bridge of a thin superconducting film as a function of an applied magnetic field. They interpreted this structure in terms of the effect of quantized "vortex" formation on the transition point of the film, as well as of longitudinal vortex motion along the bridge. We felt that this effect could be interpreted more directly, still in terms of vortices but in a manner more nearly allied to the magnetic field variation of the Josephson effect,[2] as a resistive effect in a fully superconducting sample.

To confirm this interpretation we tried an experiment analogous to Shapiro's experiment[3] on the ac Josephson effect. We shone radio-frequency power in the range $200-10^4$ Mc/sec on a number of thin film bridges and observed the resulting modifications in the direct current I-V characteristic. On the bridge shown in Fig. 1 we observed the I-V characteristic shown in Fig. 2(a) with rf frequency as a parameter, and in Fig. 2(b) with the rf power at a frequency of 810 Mc/sec as a parameter.

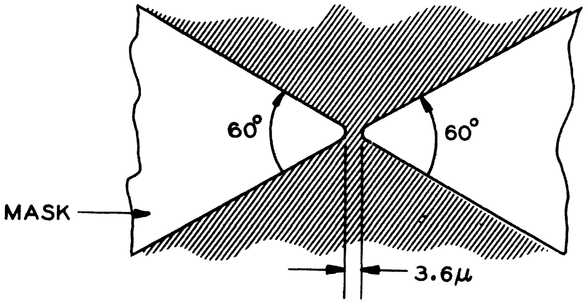

FIG. 1. Sample configuration.

We list a number of our results, some of which are evident in these curves.

(a) The steps in the I-V characteristic occur at voltages related to the frequency by the Josephson condition $mh\nu = 2eV$. A number of weaker subharmonics $mh\nu = 2neV$ occur also. Under less favorable conditions, we observe only smooth bumps at these voltages.

(b) There is a tendency to instability at low voltages which often hides the first steps.

(c) The whole phenomenon is strikingly sensitive to magnetic field, often disappearing when as little as 0.1 gauss is applied.

(d) It is noteworthy that the upper regions of the curves of Fig. 2 are linear, roughly, and parallel to the curve with very high rf power which has, as far as we can tell, been driven normal. Nonetheless they show Josephson steps at the correct voltages. This cannot occur unless there is a superconducting path (i.e., $\Delta \neq 0$)