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Electric-field-induced new features in the photoconductivity of extrinsic silicon

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Under low background radiation and at low temperatures (~ 1.4 K) the extrinsic photoresponse of phosphorus- and antimony-doped silicon exhibits a peak below the ionization energy of the impurity, when an electric field is applied. This peak grows in intensity and shifts (up to 2 meV) to lower energies as the electric field is increased. Both the position and the intensity of the peak saturate at a critical field which depends inversely on the impurity concentration. A possible explanation of the observed features is proposed.

INTRODUCTION

There has been a renewed interest in the studies of extrinsic photoconductivity or absorption spectra of semiconductors due to the observation of many exotic shallow centers other than the well-known donors and acceptors. The D^- (donor with an extra electron) and A^+ (acceptor with an extra hole) centers and their complexes,[1] molecular centers[2] and pairs of impurity centers[3] in different charge states are some examples. Structure in the photoconductivity spectra due to electron-phonon umklapp processes have been predicted[4] and observed.[5] The presence of these centers can drastically alter the characteristics of impurity based infrared photoconductive detectors. Hence, a detailed understanding of the role played by these centers is very important. These centers present an excellent opportunity for the observation of many effects due to their close analogy to the well-known hydrogen problem in atomic physics.

We present here a detailed study of the extrinsic photoconductivity spectra of silicon doped with phosphorus or antimony impurities at low tempeatures and controlled background radiation.

We report new features in the spectra which vary with the electric field across the sample. The observed spectra exhibit a peak below the ionization energy of the impurity with the applied electric field. This peak grows in intensity and shifts (up to 2 meV) to lower energies with electric field. The position and the intensity saturate at a critical field which depends inversely on the impurity concentration. Possible explanations of these observed features are proposed.

Carter *et al.*[6] have observed the photoconductivity spectra (below 400 cm^{-1}) of the phosphorus donors in silicon at 1.5 K for 10^{12} and 10^{15} impurity atoms/cm^3 as a function of applied electric field. They observe peaks corresponding to the electronic transitions from the ground state to the excited states of the impurity. However, the peaks do not appear at the energy positions observed in the absorption measurements but are always shifted to lower energies by about a linewidth. These were speculated as due to hopping of electrons between excited states of different donors. They also observed one additional line (possibly more) at 333 cm^{-1} which was attributed to molecular origin of closely spaced donor pairs. No detailed model of the process was presented. A broad peak below the ionization energy of the impurity similar to the one observed by us also seems to be present in their spectra, though it was not discussed.

Owing to the differences in impurity concentrations and possible differences in the biasing and background radiation on the samples, a direct comparison between our data and those of Carter *et al.* is not possible.

EXPERIMENTAL RESULTS

The samples were cut from single-crystal float-zone silicon. The material was purified by zone refining prior to growth. Residual impurities other than boron are vaporized or swept down to the ends of the boule. The boron concentration is in the range of 10^{13} cm^{-3}. Doping with the impurity of interest was accomplished by insertion of calculated amounts before crystal growth. The doping concentration varies along the growth axis but has a very high radial uniformity. The samples are obtained from wafers cut in the radial plane. After lapping and polishing, phosphorus was diffused into the surfaces to provide a heavily doped degenerate layer. The surfaces were then metalized sequentially with electroless nickel and electroplated indium. One of the contacts was fused to a tinned copper heat sink and the other soldered to the metal wire for the external circuitry. The infrared radiation reaches the detector transverse to these contacts via a light pipe arrangement. Room-temperature radiation was minimized by placing a cold filter in front of the sample which was immersed in liquid helium. A FS-720 Fourier transform spectrometer equipped with a dedicated computer to perform a real time analysis of the data was used.

Figure 1 (lower panel) shows the photoresponse per unit

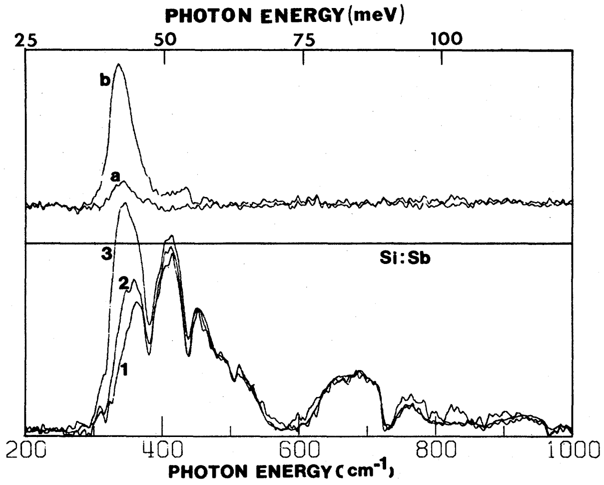

FIG. 1. (a) Lower panel: The photoresponse (unnormalized) of Si:Sb at 1.4 K for different electric fields across the sample. The impurity concentration is 1×10^{16} donors/cm^3. Note the rise in the photoresponse in the vicinity of E_I with increase in the electric field. (b) Upper panel: The electric-field-induced photoresponse extracted by subtracting from the spectrum, at a given electric field, the response measured at a very small electric field.

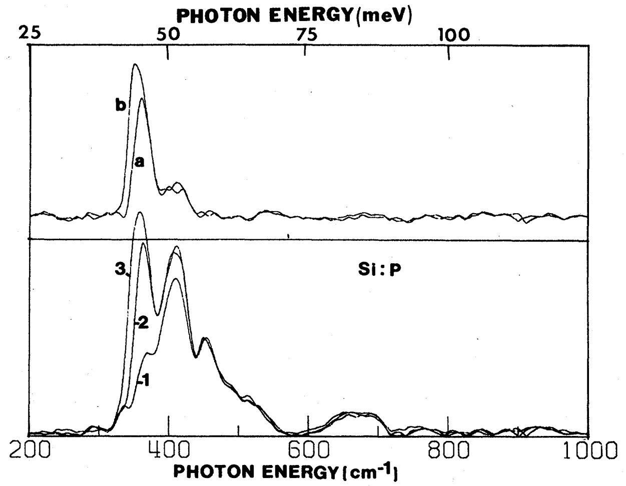

FIG. 2. (a) Lower panel: The photoresponse (unnormalized) of Si:P at 1.4 K for different electric fields across the sample. The impurity concentration is 2.4×10^{15} donors/cm^3. (b) Upper panel: The electric-field-induced photoresponse extracted by subtracting the photoresponse, at very small electric fields, from the spectrum at a given electric field.

electric field of Si:Sb for different electric fields across the sample. As the electric field increases the integrated photoresponse (area under whole spectra) also increases linearly and then saturates at higher fields. The linear increase is according to Ohm's law. As the voltage increases, the current flowing across the sample increases as long as the resistance of the sample is constant. We have corrected for this effect by dividing each spectrum by the applied electric field in Fig. 1. One can see that beyond 380 cm^{-1} the spectra are nearly identical. However, below 380 cm^{-1} the spectra are different for different electric fields. In fact, the response increases in the vicinity of the ionization edge of the impurity. We have extracted this electric-field-dependent feature by subtracting from the spectrum for a given field the photoresponse per unit electric field at the lowest electric field (zero-field spectrum) the spectrum could be measured. The electric-field-dependent photoresponse has been shown in Fig. 1 (top panel). Similar analysis for P donors for different field strengths and the electric-field-dependent peak are shown in Fig. 2.

In the case of both antimony and phosphorus donors in silicon, the electric-field-induced peak (EIP) is observed below the ionization energy of the respective donor (top panels of Figs. 1 and 2). Figure 3 shows the effect for different electric fields for a phosphorus-doped sample. The peak grows in intensity as the electric field is increased and shifts to lower frequencies. The position as well as the intensity saturate after a certain applied field. The latter decreases with increasing impurity concentration. At higher fields the integrated photoresponse over all the frequencies also seems to level off and the noise in the spectrum increases sporadically. The full width at half maximum (FWHM) of this peak is about 40 cm^{-1}.

Figure 4 shows a plot of the frequency shift of the electric-field-induced peak as a function of applied electric field, for Si:P of concentration 2.4×10^{15} cm^{-3} and Si:Sb of concentrations 1×10^{16} cm^{-3} and 8×10^{16} cm^{-3}. The peak shifts almost linearly until saturation sets in.

We now discuss briefly a possible mechanism which can explain, at least qualitatively, all the observed features in the photoconductivity spectra. At low electric field and in the presence of incident radiation, electrons excited from the donor ground state to the excited states which lie within a few kT (k is the Boltzman constant and T the temperature of the sample) of the conduction band, absorb acoustic phonons and are transferred to the conduction band where they participate in the conduction process. This process is commonly referred to as photothermal ionization. At low electric fields the electrons in the conduction band do not have sufficient energy to cause any significant impact ionization of the bound electrons in the excited states. As the electric field is increased, the electrons in the conduction band, on

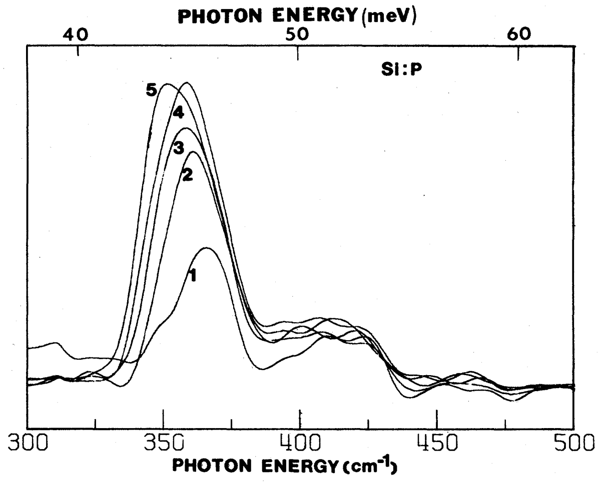

FIG. 3. Behavior of the electric-field-induced photoresponse for different electric fields for Si:P.

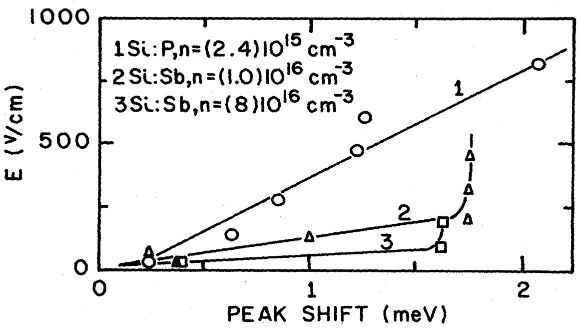

FIG. 4. Shift of the electric-field-induced peak measured from the ionization energy for Si:P with 2.4×10^{15} donors/cm^3 and Si:Sb with 10^{16} and 8×10^{16} donors/cm^3.

the average, become more energetic and cause greater impact ionization of the bound electrons in the excited states. Hence, excited states which did not have sufficient thermal energy to contribute to photothermal ionization become active to produce photoconductivity due to electric-field-induced impact ionization. This effect results in (a) an increase in the photoconductivity and (b) an apparent shift in the EIP towards lower energies. To initiate impact ionization process, however, one needs some electrons in the conduction band to begin with. Even though the temperature is small, the Boltzmann distribution allows this probability to be nonzero. Both the position and the intensity of the EIP saturate due to the fact that the electrons cannot be photothermally ionized from the excited states deeper than $n=4$ (binding energy of this level being ~ 2 meV) because their ionization energies are more than an order of magnitude larger that kT. At higher impurity concentrations, the ionization energies of the excited states are reduced due to overlap effects thus making both the photothermal and impact ionization processes more efficient at a given electric field. This accounts for the lower values of the saturation field.

Another mechanism which may also contribute to the observed behavior of the photoconductivity peak is one in which D^- centers are created by transferring electrons from the excited states to the neighboring unexcited donors. It is, however, difficult to explain all the observed features using this model.

To summarize, we have studied the extrinsic photoresponse of phosphorus- and antimony-doped silicon at low temperatures (~ 1.4 K) under low background radiation. The photoconductivity spectra exhibit a peak below the ionization energy of the impurity with the applied electric field. This peak grows in intensity and shifts (up to 2 meV) to lower energies as the electric field is increased. Both the position and the intensity depends inversely on the impurity concentration. We have proposed a model involving photothermal and impact ionization mechanisms which provides a satisfactory qualitative explanation of the observed features. More quantitative work needs to be done on this model, however, before one can be certain of its validity.

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