Observation of dielectric collapse at excited acceptors in germanium

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The dielectric constant of germanium is found to display a superlinear dependence on the concentration of photoexcited impurities. It is shown that the observed effect is due to the growth of the polarizability of the excited centers as a result of their interaction.

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It has been noted by Fan[1] that when the impurity concentration N_0 in a semiconductor is increased sufficiently, the dielectric constant ϵ begins to depend superlinearly on N_0 (the dielectric collapse). This effect is one of the mechanisms for the concentrational delocalization of impurities. The derivation from a linear dependence is observed at substantially lower concentrations than is implied by the classical Clausius-Mossotti formula,[1] which is based on the model of noninteracting, isolated centers.

The development of a highly sensitive differential technique for studying photodielectric effects associated with the excitation of impurities[2] has made it possible to study the interaction of excited centers. To do this, one need only study the magnitude of the photodielectric effect as a function of the intensity of the exciting radiation.

To observe the photodielectric collapse we used samples of germanium doped with gallium to a concentration of $(1–3)\times 10^{16}$ cm^{-3} and compensated with antimony at 2×10^{15}–1.2×10^{16} cm^{-3}. The choice of shallow acceptors as the object of study is motivated by their anomalously long lifetime τ_{ex} in the first excited state ($\tau_{ex} \sim 10^{-7}$ s).[3] The concentration N_{ex} of excited impurities grows in proportion to τ_{ex}, and, as a

consequence, so does the magnitude of the effect. Furthermore, in the scheme we have used for populating the excited states by CO_2 laser radiation ($h\nu \gg E_i$, where E_i is the ionization energy of the impurity)[2] the long lifetime τ_{ex} of the excited states enables one to eliminate the effect of screening by free carriers. In fact, the lifetime τ_c of the holes in sufficiently compensated samples is shorter by two order of magnitude than the lifetime τ_{ex} of the excited impurities (τ_c is of the order of energy relaxation time τ_{en}, which in turn is of order 10^{-9} s), so that at a relatively short time after the end of the pulse ($t \gtrsim 10^{-8}$ s) nearly all the photo-induced holes are found in the first excited state of gallium.

The concentration of the excited impurities is determined from the brightening of the sample under the exciting radiation. In fact, since τ_{ex} is much longer than τ_c, nearly all the holes that have been stripped from neutral gallium atoms are found in the first excited state of gallium, i.e., $\Delta N_0 \sim N_{ex}$. It can be shown on the basis of the theory of Kogan and Polupanov[4] that the cross section for photoionization of excited gallium atoms by CO_2 laser photons is much smaller than the corresponding cross section for the excited acceptors, and so the decrease in the absorption coefficient ($\Delta k \sim \sigma_{ph} N_{ex}$) is a measure of N_{ex}. The maximum attainable concentration of excited acceptors is about 1.5×10^{15} cm^{-3}

The results of the study of the magnitude of the photodielectric effect as a function of the concentration of excited acceptors are shown in Fig. 1. The change in the dielectric constant $\Delta\epsilon$ was detected by measuring the depth of the phase modulation of a microwave upon passage through the sample. The relative error $\Delta\epsilon/N_{ex}$ in the measurement was not more than 3%. It is seen in the figure that the superlinear growth of the photodielectric effect begins much earlier than is implied by the Clausius-Mossotti expression, which takes into account only the growth of the "specific volume" of the excited centers [$(4\pi/3\epsilon)N_{ex}\alpha_{ex}$, where α_{ex} is the polarizability of the excited acceptors]. The observed deviation of the photodielectric effect from a linear

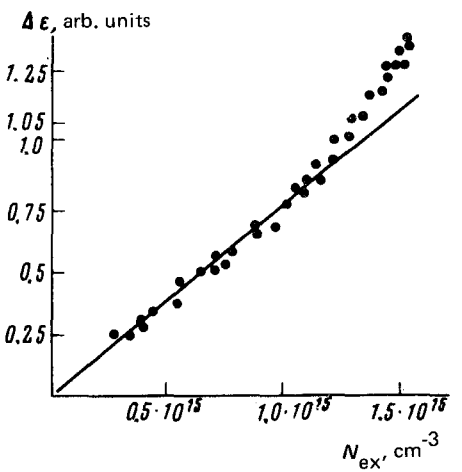

FIG. 1. Photo-induced change $\Delta\epsilon$ in the dielectric constant as a function of the concentration N_{ex} of photoexcited impurities.

dependence can be explained by a change in the polarizability of the excited acceptors, i.e., by a change in the geometry of the wave functions due to the interaction. A theoretical treatment of a possible mechanism for the observed photodielectric collapse is given by Manykin *et al.*[5]

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