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Dependence of the hole lifetime on uniaxial stress in Ga-doped Ge

O. D. Dubon
Department of Materials Science and Mineral Engineering, University of California, Berkeley, California 94720 and Lawrence Berkeley Laboratory, Berkeley, California 94720

I. Wilke and J. W. Beeman
Lawrence Berkeley Laboratory, Berkeley, California 94720

E. E. Haller
Department of Materials Science and Mineral Engineering, University of California, Berkeley, California 94720 and Lawrence Berkeley Laboratory, Berkeley, California 94720
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The effect of uniaxial stress on the hole lifetime in gallium-doped germanium single crystals has been studied by photo-Hall-effect measurements. We demonstrate that the stress dependence of the hole lifetime offers a critical test for competing models of the capture of holes by acceptors. We find that below 5 K the hole lifetime increases by over one order of magnitude upon the application of 4 kbar in a ⟨100⟩ direction. Our results show the hole lifetime to be proportional to the acoustic-phonon-scattering component of the hole mobility, in very good agreement with the cascade capture theory for Coulomb-attractive centers and in clear contradiction to the recently proposed model in which holes are directly captured into the acceptor ground state [Phys. Rev. Lett. **69**, 2839 (1992)].

The capture of mobile charge carriers by Coulomb-attractive centers has received considerable attention as it plays a significant role in the trapping and recombination processes that occur in semiconductors at low temperatures. The most widely accepted mechanism for capture has been the phonon-mediated cascade of carriers through the bound excited states of these centers.[2–4] However, the predominance of a different mechanism for the capture of holes by acceptors in germanium has recently been proposed, a mechanism in which holes are captured directly into the acceptor ground state.[1] The validity of these models traditionally has been evaluated via the comparison of the predicted temperature and impurity charge-state dependencies of the capture cross sections σ with the experimentally determined ones. This controversy is thus born out of the existence of a large body of data that yield capture cross sections exhibiting a range of temperature dependencies (σ being proportional to T^{-n} where $1<n<4$) and that can be used to corroborate either the cascade or direct capture mechanism depending on what data are considered.[1,3]

Whereas both the cascade and direct capture models predict an increase in the capture cross section with decreasing temperature T, they exhibit very different functional dependencies on the effective mass m^*. Therefore, we have performed low-temperature photo-Hall-effect measurements on germanium crystals doped with gallium acceptors and placed under uniaxial stress. By this method we have been able to study the effective-mass dependence of the hole lifetime (and necessarily the capture cross section) and can clearly distinguish between direct capture (DC) and cascade capture (CC) in this material.

The capture cross section that is based on cascade capture ($\sigma_{\rm CC}$) has a dependence on temperature and effective mass given by[5]

$$\sigma_{\rm CC} \propto T^{-4}(\mu_{\rm ac} v_{\rm th})^{-1}, \tag{1}$$

where the average thermal velocity $v_{\rm th}$ is proportional to $T^{1/2}m^{*-1/2}$ and the acoustic-phonon-scattering component of the hole mobility $\mu_{\rm ac}$ is proportional to $T^{-3/2}m^{*-5/2}$. This dependence has been used to explain earlier experimental results (data predating 1972).[3,5] More recently, the experimental capture cross sections of acceptors (including $\mathrm{CuH_2}^-$, Zn^-, and Cu^-) in germanium were measured by transient capacitance techniques.[6,7] These exhibited temperature and charge-state dependencies unlike those predicted by any phonon-mediated cascade model. These data—along with a recasting of some of the older data—had led to the direct capture model that yields a capture cross section[1]

$$\sigma_{\rm DC} \propto T^{-1}(m^*)^{-1}. \tag{2}$$

The simple relation given in Eq. (2) shows the temperature and effective-mass dependencies irrespective of the energy-loss mechanism.

Whether direct or cascade capture is the dominant mechanism has significant consequences on the hole lifetime τ. In p-type Ge at sufficiently low temperature, practically all holes are frozen out on acceptors, and the ionized acceptor concentration, i.e., the density of hole capture centers, is equal to the concentration of compensating donors N_D. In this case the hole lifetime is given by[8,9]

$$\tau = \frac{1}{\beta N_D \sigma_c v_{\rm th}}, \tag{3}$$

where β is the valence-band degeneracy (equal to 4 for zero applied stress). Because the thermal velocity is inversely proportional to $m^{*1/2}$, the lifetime depends on the effective mass as

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$$\tau_{CC} \propto \beta^{-1} \mu_{ac} \quad (4)$$

and

$$\tau_{DC} \propto \beta^{-1} m^{*3/2} \quad (5)$$

for cascade capture and direct capture, respectively. The effective-mass component of τ_{CC} is expressed in terms of μ_{ac} alone as the m^* dependence is fully contained in μ_{ac} (which is proportional to $m^{*-5/2}$). Therefore, the lifetime *increases* according to the cascade picture yet *decreases* for direct capture if the effective mass decreases.

The magnitude of the hole effective mass in Ge can be changed with uniaxial stress. The application of uniaxial stress breaks the fourfold degeneracy of the valence-band edge leaving two doubly degenerate, split bands ($\beta = 2$) in addition to the spin-orbit split-off band, which also remains doubly degenerate.[10] In the limit of high compressive stress, the constant energy surface near the band minimum, which the holes populate at low temperature, is an ellipsoid having an average (density of states) m^* equal to $0.08m_0$ compared to its zero-stress value of $0.36m_0$, where m_0 is the free-electron mass. Because the effective mass is reduced, the lifetime should *decrease* for direct capture [Eq. (5)]. However, because the carrier lifetime is in general inversely related to the effective mass according to the cascade picture, it should in this case *increase* by the application of uniaxial stress, the actual magnitude of such an increase being determined by the stress-induced changes in the scattering of holes by acoustic phonons. The interesting question regarding the effect of large uniaxial stresses on the hole lifetime in Ge has been theoretically addressed within the framework of the cascade model, and in the high-stress limit a factor of 50 increase from its zero-stress value is predicted.[11]

In order to study the effect of uniaxial stress on the hole lifetime, we have performed photo-Hall-effect measurements on p-type Ge samples that were produced from two 1-mm-thick wafers, samples A and B, having gallium concentrations of $(1.4 \pm 0.1) \times 10^{14}$ and $(1.1 \pm 0.1) \times 10^{14}$ cm^{-3}, respectively. The wafers were cut to produce a $1 \times 1 \times 5$-mm^3 parallelepiped geometry for each sample. All resulting surfaces were $\langle 100 \rangle$ oriented. Uniaxial stress up to 4.2 kbar was applied parallel to the long axis of the bar-shaped samples by a leaf-spring stress apparatus that was mounted in a Lake-Shore CT-310 continuous-flow cryostat. The sample space consisted of a closed cavity containing both the sample and a photon emitter (emissivity is 0.9), the latter needed for photo-Hall measurements. Hall coefficients were obtained for a Hall-bar sample geometry with a Keithly 110 Hall-effect measuring system and a magnetic induction of 3 kG.[12] The temperature was monitored with a calibrated Allen-Bradley, $\frac{1}{8}$-W, 1-kΩ, carbon-composite resistor.

Hole concentrations obtained from our Hall-effect measurements for sample B are shown in Fig. 1. The filled circles and squares correspond to data taken when the sampie was illuminated. The solid line was calculated using the equation[8]

$$\frac{p(p+N_D)}{N_A - N_D - p} = \frac{N_V}{\beta} \exp\left(-\frac{E_A}{kT}\right), \quad (6)$$

where p is the hole concentration, N_A and N_D are the acceptor (Ga) and donor concentrations, respectively, β is the band

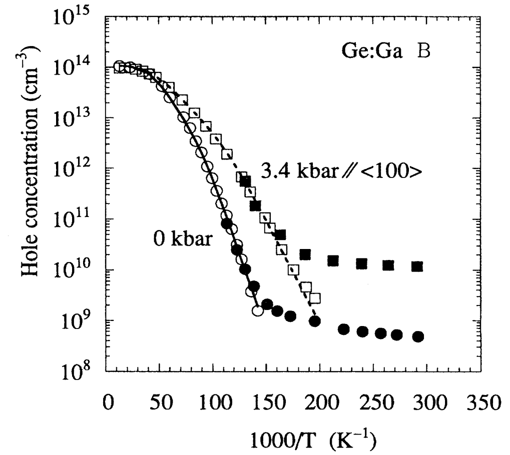

FIG. 1. Hole concentration as a function of inverse temperature obtained from Hall-effect (clear symbols) and photo-Hall-effect (filled symbols) measurements. The open circles were fitted using the following parameters: $N_A = 1.1 \times 10^{14}$ cm^{-3}, $N_D = 3.5 \times 10^{12}$ cm^{-3}, $E_A = 11.1$ meV, $N_V = 1.2 \times 10^{15} T^{3/2}$ cm^{-3}, and $\beta = 4$. The data taken at a uniaxial stress of 3.4 kbar$\|\langle 100 \rangle$ (clear squares) were fit using $E_A = 7.5$ meV, $\beta = 2$, and $N_V = 1.44 \times 10^{14} T^{3/2}$ cm^{-3} (i.e., $m^* = 0.089m_0$), while maintaining the same values for the impurity concentrations N_A and N_D.

degeneracy (equal to 4), k is the Boltzmann constant, N_V is the effective density of states , and E_A is the gallium binding energy. Therefore, a best fit to the zero-stress data yields N_A and N_D. The dashed line was obtained by using the impurity concentrations (N_A and N_D) determined from the zero-stress measurement and adjusting both N_V and E_A (which is known to decrease with stress[13,14] and whose value was confirmed by photoconductivity spectroscopy measurements) and so as to provide the best fit to the data [using Eq. (6)]. In addition, uniaxial stress reduces the valence-band degeneracy β from 4 to 2. The change in the effective density of states then reflects a change in the effective mass.

From the photo-Hall measurements (filled symbols in Fig. 1) we have estimated the hole lifetime τ_{ph}. In the region where the hole concentration is determined by the rate of photogeneration $\tau_{ph} = p^*/G^*$, where G^* is the optical generation rate and p^* is the concentration of photogenerated holes. The optical generation rate is equal to the number of photons absorbed by the sample per unit volume per unit time and is given by[9,15]

$$G^* = \frac{\displaystyle\int (\text{photon flux}) \frac{A_{\text{sample}} \alpha_{\text{sample}}}{\sum_i A_i \alpha_i} d\lambda}{[\text{sample volume}]}, \quad (7)$$

where the photon flux (photons per unit time per unit photon wavelength) is approximated by a Planck spectral distribution, A_i is the area of an absorbing surface within the sample cavity (e.g., the emitter and sample surfaces), and α_i is the corresponding absorptivity. The absorptivity of the sample α_{sample} is given by its quantum efficiency and is approximately equal to

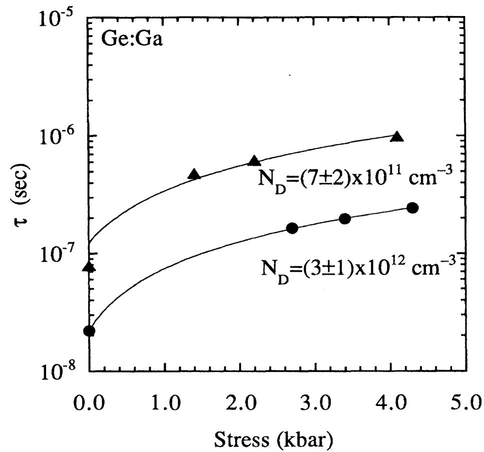

FIG. 2. Hole lifetime as a function of applied uniaxial stress. The triangles and circles denote samples A and B, respectively.

$$\alpha_{\text{sample}}=\frac{0.64[1-\exp(-\alpha^*d)]}{1-0.36\exp(-\alpha^*d)}, \tag{8}$$

where d is the sample thickness and α^* is the wavelength-dependent adsorption coefficient due to the Ga acceptors, which has been measured for unstressed and stressed Ge:Ga.[16] The numerator in Eq. (7) has been integrated in the spectral range over which the Ga centers are optically active. The calculated generation rates are 3×10^{16} and 8×10^{16} $\text{cm}^{-3}\,\text{s}^{-1}$ for the photo-Hall measurements shown in Fig. 1 in the zero-stress (filled circles) and stressed (filled squares) conditions, respectively.

The dependence of the lifetime on stress at 3.7 K for samples A and B is shown in Fig. 2. The zero-stress values of the hole lifetime agree within a factor of 2 with previous results for Ge doped with shallow acceptors.[17] For the largest applied stress of 4.2 kbar, the lifetime has increased by one order of magnitude compared to the zero-stress value. Such an increase has been observed throughout the temperature range over which photo-Hall measurements were made (Fig. 1). It is clear from Fig. 2 that the direct capture mode does not describe the effect of stress on the hole lifetime that we have observed, as the lifetime *has increased* by the application of stress even though the direct capture model would predict a decrease in τ.

The hole lifetime exhibits a dependence on m^* as indicated in Fig. 3. The ratio between $\beta\tau$ and the zero-stress value of $\beta\tau$ has been plotted in order to show the functional dependence of τ on the effective mass alone. In addition, we have studied the stress dependence of the mobility μ (Fig. 4) in the context of acoustic-phonon (ac), ionized-impurity (ii), and neutral-impurity (ni) scattering, whereby $1/\mu \approx 1/\mu_{\text{ac}}+1/\mu_{\text{ii}}+1/\mu_{\text{ni}}$.[18–20] From these results, we have estimated the increase of μ_{ac} as a function of stress (and effective mass). These values are plotted in Fig. 3 (crosses) by the use of Eq. (4). The solid line in Fig. 3 is fit to this data yet provides an excellent fit to the lifetimes determined from the photo-Hall measurements (circles and triangles) as well. Thus, we find from the *independently obtained* experimental lifetimes and mobilities that

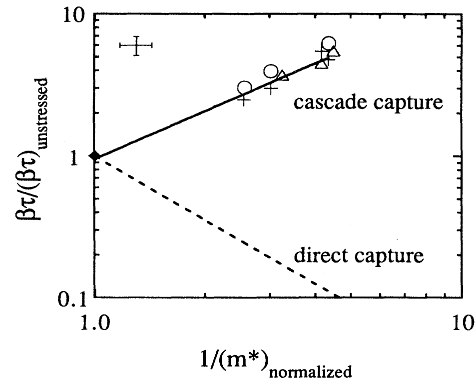

FIG. 3. Product of the hole lifetime and band degeneracy as a function of the inverse normalized effective mass $[(m^*)_{\text{normalized}}=m^*/(m^*)_{\text{unstressed}}]$. The circles denote sample A while the triangles are from sample B. The solid line has been obtained by fitting the scaled μ_{ac}'s (crosses) and reflects the change in the lifetime that is expected from cascade-capture theory [Eq. (4)].

$$\tau_{\text{ph}}\propto\beta^{-1}(\mu_{\text{ac}})_{\text{exp}}. \tag{9}$$

The agreement between Eqs. (4) and (9) provides a very compelling argument supporting the dominance of phonon-mediated cascade capture of holes by gallium acceptors in Ge.

Finally, this large increase in carrier lifetime is not restricted to germanium doped with gallium, a shallow monovalent impurity. We have performed similar measurements with Be-doped Ge and have observed an equally large increase in lifetime over a larger temperature range (4–9 K).

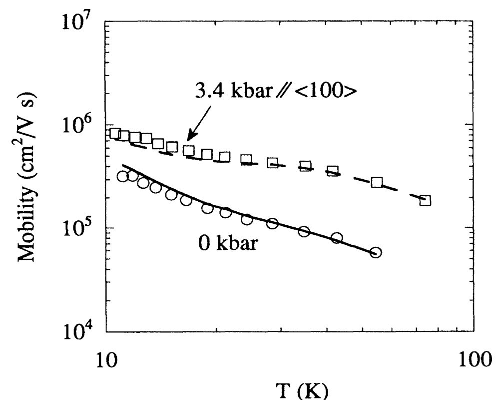

FIG. 4. Mobility as a function of temperature obtained from Hall-effect measurements with the corresponding concentrations shown in Fig. 1. The circles are in good agreement with the mobility expected for p-type Ge (solid line) (Ref. 21). Increasing μ_{ac} by a factor of 5.5 and scaling μ_{ii} and μ_{ni} with the proper effective mass ($m^*=0.089m_0$ and $m_H=0.14m_0$ at 3.4 kbar) produce a good fit to the data for stressed Ge:Ga at the higher temperatures where scattering by acoustic phonons dominates—compare the squares with the dashed line.

Beryllium is a double acceptor having a first ionization potential of 24.8 meV. Our results on this system are largely qualitative at this time, yet they do suggest that the capture of holes by deeper acceptors is more complex compared to simple shallow levels as suggested by the recent data of Darken and co-workers.[6,7] Work on this system and other deeper acceptors is in progress.

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