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Author

Markiewicz, Robert S.

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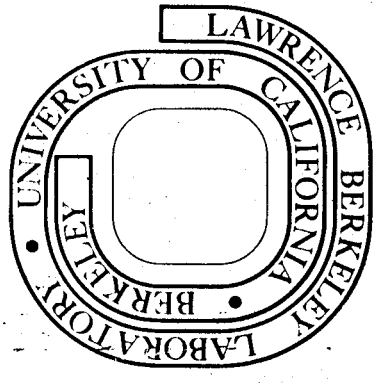

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Robert S. Markiewicz

Physics Department, University of California, Berkeley, CA 94720

and

Materials and Molecular Research Division
Lawrence Berkeley Laboratory, Berkeley, CA 94720

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ABSTRACT

Deformation potentials are calculated for electron-hole droplets in Ge and compared to the values for degenerate n- or p-doped Ge. Due to the conduction band anisotropy and the presence of an equal number of electrons and holes, it is found that screening effects are substantially reduced, but that there are strong anisotropies in coupling to various phonon modes.

Deformationspotentiale für Elektron-Loch Tropfen in Germanium wurden errechnet und mit den Werten für degeneriertes n- und p-Ge vergleichen. Wir finden, dass wegen der Leitungsbandanisotropie und der Anwesenheit einer gleichen Zahl in Elektronen und Löchen die Abschirmeffekte stark abgeschwacht werden, dass aber starke Anisotropien in der Kopplung zu den verschiedenen Phononzweigen bestehen.

There has been much recent interest in the interaction between electron-hole droplets (EHD) [1] and lattice vibrations in Ge. Both the interactions with acoustic phonons [2,3] and with ultrasonic waves [4,5,6] have been studied. Furthermore, it has recently been shown that an intense stream of phonons can move EHD over macroscopic distances [7,8]. It is thought that such a "phonon wind" may be responsible for producing the cloud of EHD observed in unstressed Ge [7,9].

Keldysh [10] has calculated the electron-phonon deformation potential scattering rate, treating the drop as a metal, but ignoring any effect of the carriers on the deformation potentials. However, a simple estimate using a single isotropic carrier type would suggest that the deformation potential should be screened, reducing the electron-phonon collision rate by orders of magnitude.

This paper presents a calculation of the screened deformation potential inside an EHD, incorporating the band structure of Ge. It is found that, due to the multivalley structure of the conduction band, and the presence of both holes and electrons, only a fraction of the deformation potential is screened. For the holes, the deformation potential is actually significantly enhanced. In addition, new effects arise because the drop is a liquid. These effects include a bunching of charge at twice the frequency of the sound wave, although it is likely that such effects could only be observed in larger drops than can presently be formed.

The present calculation describes the correct deformation potentials inside an EHD. From these potentials, it is straightforward to calculate

the average electron-phonon collision rate for a particular phonon mode [10], and from this to estimate the net acoustic phonon scattering time [11] for the drop.

For a simple metal (single carrier type with isotropic mass) the treatment of screening effects is standard [12,13], and is here briefly summarized for completeness. A phonon, with sinusoidally varying stress field $\overleftrightarrow{\varepsilon} = \overleftrightarrow{\varepsilon}_o e^{i\vec{q}\cdot\vec{r}}$, locally alters the energy of an electron in the state $\vec{k}$ by an amount

$$\delta E_{\vec{k}}(\overleftrightarrow{\varepsilon}) \equiv E_{\vec{k}}(\overleftrightarrow{\varepsilon}) - E_{\vec{k}}(0) = C\Delta \tag{1}$$

where Δ = Trace $(\overleftrightarrow{\varepsilon})$ is the local lattice dilation, and C is a deformation potential, which can be considered independent of wave number $\vec{k}$. If the electrons were frozen in place, this strain would produce a local change in the electronic Fermi level by an amount

$$\delta E_F = (C - \frac{n}{D_F})\ \Delta \tag{2}$$

where n is the electronic density and D_F is the density of states at the Fermi energy. The first term is an average of Eq. (1) over the Fermi surface, while the second is due to the change in density of the positive ions. The electrons flow to regions of lower Fermi level, creating a negative electrical potential which repels other electrons, and equalizes the Fermi level throughout the drop. An electronic density variation $\delta n_q e^{i\vec{q}\cdot\vec{r}}$ produces a potential $\frac{U_q}{e} e^{i\vec{q}\cdot\vec{r}}$, where, by Poisson's equation

$$U_q = \frac{4\pi e^2}{q^2 \varepsilon_o} \delta n_q \tag{3}$$

(ε_o is the dielectric constant of bulk Ge).
Thus the total variation of Fermi level in the crystal is

$$\left[\delta E_F + \frac{\delta n_q}{D_F} + U_q\right] e^{i\vec{q}\cdot\vec{r}} \tag{4}$$

the second term being the direct change in Fermi level due to the charge bunching, and the last term due to the induced potential. Eq. (4) must be constant throughout the metal [14], and if the wave is many cycles in length, the constant value will average to zero. Thus

$$U_q = \frac{-\delta E_F}{1+q^2/\kappa_{FT}^2} \tag{5}$$

where $\kappa_{FT}=\sqrt{4\pi D_F e^2/\varepsilon_o}$ is the Fermi-Thomas screening wave number. Now the total energy change seen by a single electron is

$$\delta E_{\vec{k}\ net} = \delta E_{\vec{k}}\ (\overleftrightarrow{\varepsilon}) + U_q \tag{6a}$$

$$= \left[+\frac{n}{D_F}\Delta + \frac{q^2}{\kappa_{FT}^2} C\Delta\right] \Big/ \left[1+q^2/\kappa_{FT}^2\right] \tag{6b}$$

In calculating the electron-phonon scattering rate, the net deformation potential, Eq. (6), must be substituted into the electron-phonon matrix element. In a metal, $q << \kappa_{FT}$, and the lattice deformation potential is completely screened, and replaced by $+\frac{n}{D_F} = +\frac{2}{3} E_F$ for a spherical band.

For an electron-hole drop in Ge, we have $q \leq 2k_F \sim 2 \times 10^6 cm^{-1}$, $\kappa_{FT} = 4 \times 10^6 cm^{-1}$, and $E_F = 2.4$ meV (electrons). Thus the scattering rate, proportional to the square of the matrix element, is reduced by a factor of $(\kappa_{FT}/q)^4 = 16$ for even the most energetic phonons. Since C ~ 5 eV (see below), the term $\frac{2}{3} E_F$ is negligible [15].

The complicated band structure of Ge, and the fact that there are equal numbers of electrons and holes inside the EHD, both combine to reduce the importance of screening effects. The electrons in an EHD are distributed among four equivalent conduction band minima located at the edge of the Brillouin zone along ⟨ 111 ⟩-directions (the L-points). For any particular valley (labelled i), the deformation potential is not merely a scalar multiple of the dilation, but is represented by:

$$\delta E_{\vec{k}}^{(i)}(\overleftrightarrow{\varepsilon}) = (\Xi_d + \frac{1}{3}\Xi_u)\,\Delta + \Xi_u(\hat{a}_i \cdot \overleftrightarrow{\varepsilon} \cdot \hat{a}_i - \frac{1}{3}\Delta) \qquad (7)$$

where Ξ_d and Ξ_u are the deformation potentials introduced by Herring and Vogt [11] (Table 1) and $\hat{a}_i$ is a unit vector pointing along the i^{th} ⟨ 111 ⟩-conduction valley. At any point in space, the Fermi energy will change by the average of Eq. (7) over all four Fermi surfaces. Thus

$$\delta E_F^e = (\Xi_d + \frac{1}{3}\Xi_u)\,\Delta \equiv E_1 \Delta \quad . \qquad (8)$$

In repeating the analysis leading to Eq. (6), it is clear that only the dilational part ($\propto E_1$) of the deformation potential is screened, while shear deformations are not. Thus transverse phonons (for which the lattice dilation vanishes) are not screened [16]. Table 2 lists the

unscreened deformation potentials in Ge (col. 1); for comparison, column 2 gives the screened values which would occur in a heavily doped n-type Ge sample (electrons degenerate).

A similar situation holds in the valence band, which has a two-fold degenerate maximum (ignoring spin) at the center of the Brillouin zone (Γ-point). Because of the degeneracy, the deformation energy explicitly depends on $\vec{k}$:

$$
\begin{aligned}
E^h_{\pm}(\vec{k}) &= Ak^2 + a\Delta \pm \sqrt{E^2_{kk}+E^2_{\varepsilon k}+E^2_{\varepsilon\varepsilon}} \\
E^2_{kk} &= B^2k^4 + C^2(k_x^2k_y^2+\text{c.p.}) \\
E^2_{\varepsilon k} &= Bb[3(k_x^2\varepsilon_{xx}+\text{c.p.}) - k^2\Delta] + 2d\sqrt{3B^2+C^2}\ [\varepsilon_{xy}k_xk_y + \text{c.p.}] \\
E^2_{\varepsilon\varepsilon} &= \frac{1}{2}\,b^2[(\varepsilon_{xx}-\varepsilon_{yy})^2 + \text{c.p.}] + d^2[\varepsilon^2_{xy} + \text{c.p.}]
\end{aligned}
\qquad (9)
$$

where $\pm$ refer to the two degenerate bands, A, B, and C are the inverse mass parameters [17], a, b, and d the deformation potentials introduced by Picus and Bir [18] (Table 1), and c.p. means cyclic permutation of the indices x, y, and z (which refer to crystalline $\langle 100 \rangle$-directions). For small strains, the average deformation energy due to the b- and d-terms vanishes for each band. Thus:

$$\delta E^h_{F\pm} = a\Delta \qquad (10)$$

and again, only dilational deformations are screened. Table 3 lists the unscreened and screened hole deformation potentials in a sample of

metallic p-doped Ge. An average hole deformation potential is defined in Table 3 as the root mean square average over all possible directions of hole momentum. (The number actually calculated is an approximation to this, averaged only over the principal symmetry directions - ⟨100⟩, ⟨110⟩, and ⟨111⟩.)

Inside an EHD, we must consider the simultaneous presence of both electrons and holes--in particular, there can be simultaneous bunching of both carriers with no net charge buildup, and screening will be reduced even more. However, since an EHD is a liquid, with strong correlations between particles, a density fluctuation will set up a pressure gradient which tends to keep the density uniform.

In an EHD the chemical potential, $\mu = \mu_e + \mu_h$, must be constant throughout the drop. The chemical potential may be written as

$$n\mu = G = nE + p \tag{11}$$

$$E = E_o + \frac{1}{2} E''_o (n-n_o)^2 \tag{12}$$

$$p = n^2 \frac{\partial E}{\partial n} = n^2 E''_o (n-n_o) \tag{13}$$

where E is the energy, G the Gibbs free energy per unit volume, and p the pressure inside the drop, and n_o and E_o are the equilibrium values of the pair density and energy. The total change in chemical potential under uniaxial stress is

$$\delta\mu = (E_1 + a)\,\Delta \tag{14}$$

A spatial variation in $\delta\mu$, caused by a phonon of wave-vector $\vec{q}$, will cause the electrons and holes to bunch up. This bunching will further modify the chemical potential due to compressional effects:

$$\delta\mu_p = \frac{\Delta p}{n} = \frac{1}{2}\, n_o E_o''\, (\delta n_e + \delta n_h) \tag{15}$$

and to electrostatic effects:

$$\delta\mu_e = U_q = \frac{4\pi e^2}{q^2 \varepsilon_o}\, (\delta n_e - \delta n_h) \tag{16}$$

In order to split $\delta\mu_p$ into separate electron and hole terms, we follow the ansatz of Rice [19], and divide the part of $\delta\mu_p$ due to exchange and correlation equally between electrons and holes. Thus $\delta\mu_p = \frac{1}{2}\, n_o E_o^{(2)}\, (\delta n_e + \delta n_h) + \delta n_e / D_F^e + \delta n_h / D_F^h$, where $E_o^{(2)}$ can be calculated from the theoretical value of E_o'' by setting $\delta n_e = \delta n_h$.

The net electron and hole chemical potentials must both be spatially constant inside the drop, so that

$$E_1 \Delta + \frac{1}{4}\, n_o E_o^{(2)} (\delta n_e + \delta n_h) + \frac{4\pi e^2}{q^2 \varepsilon_o}\, (\delta n_e - \delta n_h) + \frac{\delta n_e}{D_F^e} = 0 \tag{17}$$

$$a\Delta + \frac{1}{4}\, n_o E_o^{(2)} (\delta n_e + \delta n_h) - \frac{4\pi e^2}{q^2 \varepsilon_o}\, (\delta n_e - \delta n_h) + \frac{\delta n_h}{D_F^h} = 0 \tag{18}$$

These equations may easily be solved in general, but simplify in the limit of perfect screening ($q^2 \to o$, U finite; thus $\delta n_e = \delta n_h$):

$$U = \left[\frac{(E_c+E_F^e)a - (E_c+E_F^h)E_1}{2E_c + E_F^e + E_f^h} \right] \Delta \tag{19}$$

$$\frac{\delta n_e}{n_o} = - \frac{3}{2} \frac{(E_1+a)\Delta}{2E_c+E_F^h+E_F^e} \tag{20}$$

These results use the relation $n/D_F = \frac{2}{3} E_F$ and the definition $E_c \equiv \frac{3}{4} n_o^2 E_o^{(2)}$. For unstrained Ge, E_F^e = 2.4 meV, E_F^h = 3.7 meV, E_c = -2.3 meV [20], so that, using Table 1, $\delta n_e = 9500\ n_o \Delta$, U = 5.3Δ eV.

Since the change in compressional energy is quadratic in δn, then to first order, the net energy change experienced by a carrier will, as in a metal, be given by:

$$\delta E^{(e)} = \delta E^{(e)}_{\vec{k}} (\overleftrightarrow{\varepsilon}) + U \tag{21}$$

$$\delta E^{(h)} = \delta E^{(h)}_{\vec{k}} (\overleftrightarrow{\varepsilon}) - U \tag{22}$$

In Tables 2 and 3, the resulting screened deformation potentials for electrons and holes in EHD (col. 3) are compared to the unscreened values (col. 1) and to the screened values in highly doped Ge (col. 2). When both electrons and holes are present, both cannot be screened simultaneously. In unstrained Ge it is primarily the electrons which are screened (compare cols. 2 and 3). Under a ⟨ 111 ⟩-stress, electrons

and holes are about equally screened (see col. 5 and the discussion below).

Several additional comments should be made in regard to the above calculation. First, the calculation explicitly assumes that there are many phonon wavelengths inside the drop. If the wavelength is large compared to the drop, then the chemical potential will be essentially constant throughout the drop, and there will be no charge bunching or induced electric fields. In Eqs. (17)-(18), $\delta\mu$ should be replaced by $\delta\mu - \overline{\delta\mu}$, where $\overline{\delta\mu}$ is the average value of $\delta\mu$ inside the drop. As $qa \to 0$ (where a is the drop radius), $\delta\mu \to \overline{\delta\mu}$, and there are no screening effects. In unstressed Ge the drops are small, a ~ 1-10 μm, so that the drop diameter is less than the sound wavelength for $\omega \lesssim 2\pi C_s/a \simeq 1.5 \times 10^{10}\text{sec}^{-1}$ (if a = 2 μm, and $C_s = 5 \times 10^5$cm/sec). This frequency is within the range presently studied by ultrasonic attenuation [4]. It is an order of magnitude lower than typical thermal phonon frequencies $k_B T/\hbar$ at 2K, and so these screening effects should be taken into account in calculating the lattice scattering rate. In inhomogeneously stressed Ge it is possible to make drops much larger [21], up to a ~ 400μ, so that screening effects could be observed for ultrasonic frequencies as low as 20 MHz. However, in this case the deformation potentials will have different values, as discussed below.

There is an additional contribution to the deformation energy of an EHD which has so far been overlooked. The binding energy of the EHD is enhanced by the multivalley structure of the conduction band and the degeneracy of the valence band, which allow extra electrons and holes to be accomodated in low kinetic energy states without violating the

Pauli principle. A strain which splits the valley degeneracy will therefore decrease the drop binding energy, adding an extra component to the (homogeneous) deformation energy. This effect is quite large for a static deformation: for small uniaxial stresses, the EHD energy does not shift parallel to the bulk Ge band edges [22]. These carrier repopulations could have quite unusual effects in a sound wave. For example, a compression along a crystalline ⟨ 110 ⟩-direction will raise two bands in energy with respect to the other two, while a tension would lower these same bands. Thus for a longitudinal ⟨ 110 ⟩-phonon, either a rarefaction or compression would tend to lower the drop binding energy, so that μ would change at twice the frequency of the phonon. Furthermore, transverse waves could also induce a spatially varying μ. However, at low temperatures, the electron intervalley scattering rate is so low that repopulation effects should be observable only in very low frequency waves. But for these waves, the wavelength will be large compared to the EHD radius, and consequently no screening should be observed (see the Appendix).

There will be similar changes due to interband transfer between the two degenerate hole bands. In this case the interband transitions should be rapid enough to affect the deformation energy. While it is clear [22] that the strain-induced splitting of the holes has a large effect on the EHD binding energy, it is not clear how this energy change varies with stress in different directions. The simplest assumption is that the energy lowering is proportional to the splitting of the two hole band edges [23]: $\delta\mu_{ib} = +2E_{\varepsilon\varepsilon}\alpha_v$ with $\alpha_v = 1.24$ [21]. The corrected deformation potentials (Tables 2 and 3, col. 4) can now be

calculated by adding $\Delta\mu_{ib}$ to $a\Delta$ in Eq. (19). Note that now the transverse deformation potentials are also screened.

It should further be pointed out that the Fermi-Thomas screening length is modified inside an EHD. Thus for finite q, Eq. (19) should be replaced by $U = U_o/(1+q^2/\kappa'^2_{FT})$, where U_o is given by Eq. (19), and

$$\frac{4\pi e^2}{\kappa'^2_{FT}\varepsilon_o} = \frac{1}{2}\left[(E_c+E_F^e)/D_F^h + (E_c+E_F^h)/D_F^e\right]/(2E_c+E_F^e+E_F^h) \qquad (23)$$

Finally, the presence of a large (static) uniaxial stress will further modify the above results. For example, a compressional stress along a ⟨111⟩-axis $|T| > 3$ kg/mm^2 will lower the corresponding conduction band valley enough to completely depopulate the other three valleys. In this case the averaging over the four bands which led to Eq. (8) will clearly not occur, and δE_F^e will be given by the full Eq. (7). The resulting deformation energies in this case are again listed in Tables 2 and 3 (col. 5) [24].

The above results should be susceptible to experimental verification. For example, a longitudinal ultrasonic wave propagated along a ⟨100⟩-axis would be perfectly screened (and hence suffer little attenuation) in either n-doped or p-doped metallic Ge. But inside an EHD, with equal numbers of mobile electrons and holes, the wave is attenuated as strongly in this as in any other direction [4], in accord with the results of Tables 2 and 3. Also, the large difference between the screened (cols. 3 or 4 of Tables 2, 3) and unscreened (col. 1) deformation potential scattering can be studied by varying the

frequency of the ultrasonic wave. If the sound wavelength is large compared to the drop radius, the deformation potential will be unscreened whereas the screened potential should be used in the opposite limit ($qa \to \infty$). Recent experiments [8] using heat pulses to study the phonon wind effect show great promise of actually measuring the deformation potentials for the various phonon propagation modes.

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Appendix: Intervalley Electron Scattering

At low temperatures, the electron intervalley scattering rate is dominated by electron-electron collisions involving carriers in bands with opposite momenta [25]. In Ref. [25], it is shown that if the $\langle 11\bar{1} \rangle$-valley is raised in energy with respect to another valley by an energy $\Delta E >> E_F$, then the population $n_{11\bar{1}}$ will decrease according to

$$\frac{\partial n_{11\bar{1}}}{\partial t} = -4\pi n_{11\bar{1}} n_{\bar{1}\bar{1}\bar{1}} N(\Delta E) I^2 = -\frac{[n_{11\bar{1}}(t)]^2}{\tau n_{11\bar{1}}(o)}$$

where I is a matrix element, $N(\Delta E) \propto (\Delta E)^{1/2}$ is the density of final states, and τ is estimated to be 2.5×10^{-9}sec, for $\Delta E = 20$ meV.

For a small strain splitting $\Delta E << E_F$, the excess population $\delta n_{11\bar{1}}(\Delta E)$ will relax according to

$$\frac{\partial \delta n_{11\bar{1}}(\Delta E)}{\partial t} = -4\pi \delta n_{11\bar{1}}(\Delta E) \delta n_{\bar{1}\bar{1}\bar{1}}(\Delta E + kT) N(E_F) I^2$$

$$= -\frac{\delta n_{11\bar{1}}(\Delta E)}{\tau'}$$

where we have assumed $\Delta E << kT$, and estimate $\tau' = 4.7 \times 10^{-9} \frac{T_f}{T}$ sec = 6.8×10^{-8}sec at T = 2K. For a longitudinal wave ($C_s = 5 \times 10^5$cm/sec) of frequency $\omega = 1/\tau'$, the wavelength $\lambda = 2.1$ mm, which is larger than the largest EHD observed.

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Table 1. Deformation potentials in bulk Ge.

$$\Xi_d = -12.3 \text{ eV}^a$$

$$\Xi_u = +19.3 \text{ eV}^a$$

$$a = (-3 \text{ eV})^{b,c}$$

$$b = -2.1 \text{ eV}^b$$

$$d = -4.6 \text{ eV}^b$$

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c. The value of a is not well known. See the discussion in Ref. b, especially Tables 5-1 and 5-2.

Table 2. Screened deformation potentials for electrons in EHD in Ge.

Column (1) lists the unscreened deformation potentials for various polarizations and propagation directions of lattice vibration. Column (2) shows the perfectly screened ($q \to 0$) deformation potentials in a metallic n-doped Ge sample (i.e.: same electron density as in an EHD, but no holes). Columns (3) and (4) show the perfectly screened deformation potentials inside an unstressed EHD: column (3) represents Eq. (21); column (4) includes the correction for hole interband scattering. Column (5) corresponds to column (3), but in the presence of a sufficiently large $\langle 111 \rangle$ stress that all electrons are in a single conduction band. Note that electrons in different valleys may experience different deformation potentials for a given phonon. The valleys are labelled: $1 = \langle 111 \rangle$, $2 = \langle 11\bar{1} \rangle$, $3 = \langle 1\bar{1}1 \rangle$, $4 = \langle 1\bar{1}\bar{1} \rangle$.

Longitudinal Waves

deformation potential = $E_{\vec{k}}/\Delta$

propagation direction	non-zero strains	(1) one electron	(2) n-doped	(3) unstrained EHD	(4) unstrained EHD	(5) strained EHD	electron valleys
⟨ 100 ⟩	$\varepsilon_{xx} = \Delta$	$E_1 = -5.9$ eV	0	-0.6	-1.0	-4.4	
⟨ 110 ⟩	$\varepsilon_{xx}=\varepsilon_{yy}=\varepsilon_{xy}=\Delta/2$	$E_1 \pm \frac{1}{3}\Xi_u = \begin{cases} +0.5 \\ -12.3 \end{cases}$	6.4 -6.4	+5.8 -7.0	+5.4 -7.4	-1.3 -7.6	1,2 3,4
⟨ 111 ⟩	$\varepsilon_{ij} = \Delta/3$	$E_1 + \frac{2}{3}\Xi_u = +6.9$	12.8	+12.2	+11.7	1.9	1
		$E_1 - \frac{2}{9}\Xi_u = -10.1$	-4.3	-4.8	-5.3	-6.5	2-4

Transverse Waves

propagation direction	polarization	strains	(1) - (3)	(4)	(5)	electron valleys
⟨ 100 ⟩	⟨ 010 ⟩	$\varepsilon_{xy} = \Delta$	$\pm\frac{2}{3}\Xi_u = \pm 12.8$	12.0 -13.6	±6.4	1,2 3,4
⟨ 110 ⟩	⟨ $1\bar{1}0$ ⟩	$\varepsilon_{xx} = -\varepsilon_{yy} = \Delta$	0	-0.6	0	
	⟨ 001 ⟩	$\varepsilon_{xz}=\varepsilon_{yz} = \Delta/2$	0	-0.6	0	3,4
			$\pm\frac{2}{3}\Xi_u = \pm 12.8$	12.2 -13.4	±6.4	1 2
⟨ 111 ⟩	⟨ $1\bar{1}0$ ⟩	$\varepsilon_{xx} = -\varepsilon_{yy}$	0	-0.8	0	1,2
		$= 2\varepsilon_{xz} = -2\varepsilon_{yz} = \Delta$	$\pm\frac{2}{3}\Xi_u = \pm 12.8$	12.0 -13.6	±6.4	3 4

Table 3. Screened deformation potentials for holes in EHD in Ge.

The columns have the same interpretation as in Table 2. Because the deformation potential is a root-mean-square average over directions in $\vec{k}$-space, the signs are all taken as positive. Note that when only one electron ellipsoid is occupied (column 5), the hole deformation potential depends on the relative orientation of the sound propagation direction and the major axis of the occupied ellipsoid.

Longitudinal Waves

deformation potential = $\delta E_{\vec{k}}/\Delta$

propagation direction	(1) one electron	(2) p-doped	(3) unstrained EHD	(4) unstrained EHD	(5) strained EHD	electron valleys
⟨100⟩	3.2	1.2	8.4	8.7	4.6	
⟨110⟩	3.8	2.4	8.6	9.0	2.6 7.9	1,2 3,4
⟨111⟩	3.9	2.6	8.7	9.1	3.2 7.0	1 2-4

Transverse Waves

propagation direction	polarization	(1)-(3)	(4)	(5)	electron valleys
⟨100⟩	⟨010⟩	4.4	4.5	7.8	
⟨110⟩	⟨1$\bar{1}$0⟩	3.2	3.3	3.2	
	⟨001⟩	3.1	3.2	3.1 7.1	3,4 1,2
⟨111⟩	⟨1$\bar{1}$0⟩	4.5	4.6	4.5 7.8	1,2 3,4

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TECHNICAL INFORMATION DIVISION
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720