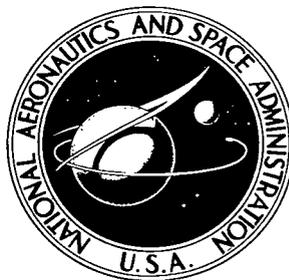


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SIMPLIFIED THEORY AND TRANSDUCER POTENTIALITIES OF THE "PINCH EFFECT" IN SEMICONDUCTORS

by Ernest E. Pittelli and Wilhelm Rindner

Electronics Research Center

Cambridge, Mass.



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ABSTRACT

The recently reported "electric pinch effect" in anisotropic semiconductors is analyzed theoretically with emphasis on the underlying physical phenomena. The theory is generalized (a) to apply to extrinsic semiconductors and (b) to encompass effects in the direction transverse to stress and electric field. In extrinsic material the magnitude of the pinch effect is reduced by the ratio of minority to majority carriers. In the transverse direction a potential difference is generated by two essentially independent mechanisms: (1) highly surface-dependent diffusion caused by a stress-dependent concentration gradient of free carriers, and (2) surface-independent transverse piezoresistance. The potential and limitations in the utilization of the pinch effect for electromechanical transducers are examined.

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SUMMARY

The recently reported "electric pinch effect" in anisotropic semiconductors is analyzed theoretically with emphasis on the underlying physical phenomena. The theory is generalized (a) to apply to extrinsic semiconductors and (b) to encompass effects in the direction transverse to stress and electric field. In extrinsic material the magnitude of the pinch effect is reduced by the ratio of minority to majority carriers. In the transverse direction a potential difference is generated by two essentially independent mechanisms: (1) highly surface-dependent diffusion caused by a stress-dependent concentration gradient of free carriers, and (2) surface-independent transverse piezoresistance. The potential and limitations in the utilization of the pinch effect for electromechanical transducers are examined.

INTRODUCTION

A newly reported electromechanical interaction in intrinsic semiconductors, the so-called pinch effect (PE), has yielded resistance changes two orders of magnitude larger than those obtainable from piezoresistance (ref. 1). An effect of such magnitude obviously suggests intriguing new electromechanical transducer potentialities; however, the detailed physical origins of this PE, depicted in Figure 1, are quite involved, and a realistic assessment of device possibilities and limitations requires a good understanding of the underlying physics beyond mere recognition of the impressive magnitude of the effect.

Presently, one objective, therefore, is to present a simplified, yet realistic, analytical description of the PE with emphasis on the physics underlying the mathematical formalism. Beyond this, the theory will be extended to extrinsic material, a new transverse mode (TPE) of the pinch effect will be proposed and shown to possess several advantages compared to the original longitudinal mode (LPE), and a general, albeit limited, characterization of PE device requirements, capabilities, and limitations, will be derived.

To anticipate the conclusions of this report: the PE offers the potential for transducers of high sensitivity and permits the use of materials not suited for conventional piezoresistive devices. These advantages are obtained at the expense of stringent

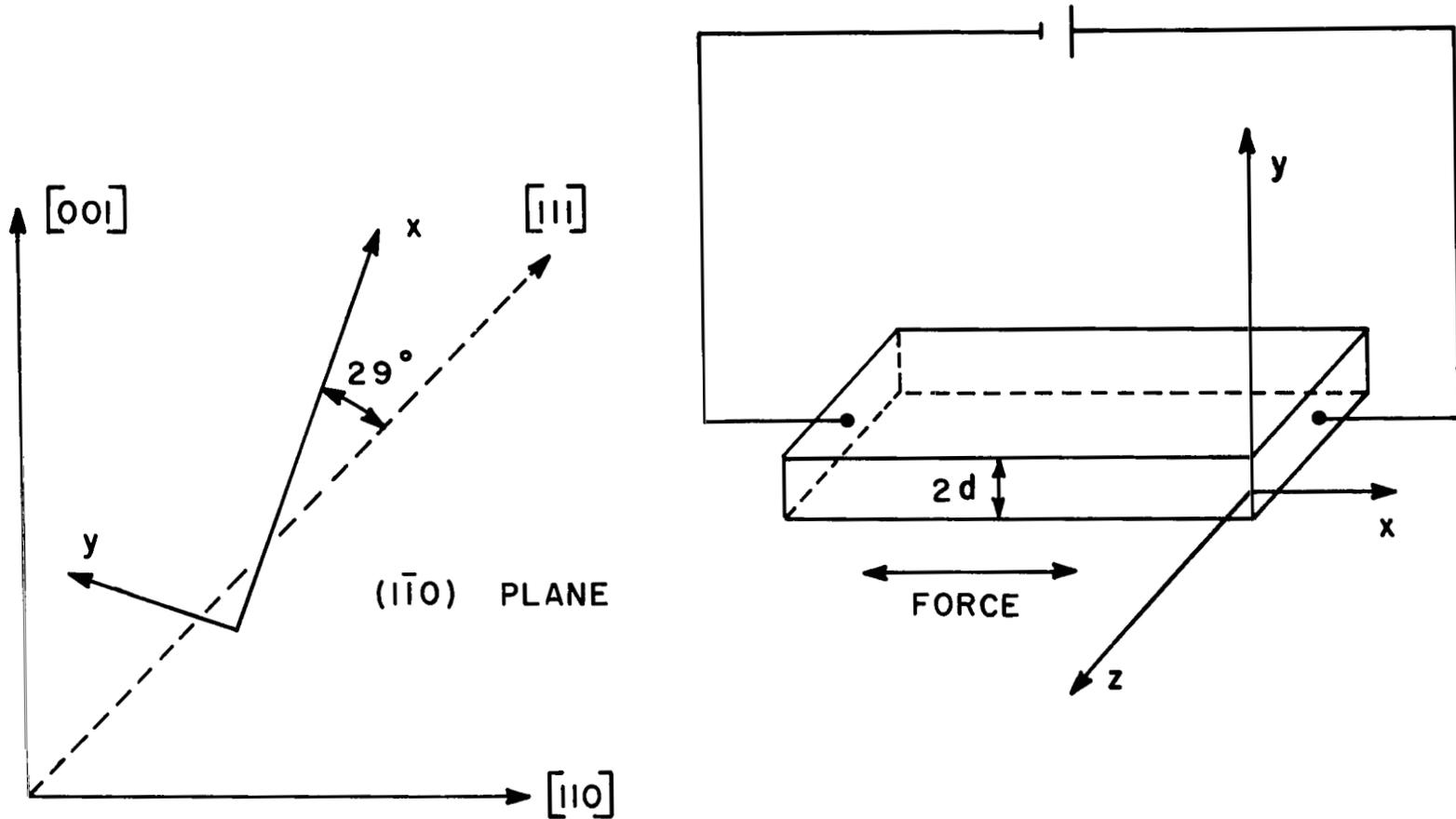


Figure 1.- Optimal sample orientation and direction of stress and electric field for observation of the "pinch effect." Stress causes a large change of current j_x and the generation of a transverse voltage along the y -direction (ref. 1).

crystallographic orientation requirements, stringent control of surface recombination velocities, a high frequency response limit in the kHz range, and non-linear stress dependence. Whether or not PE devices will excel in any given application will depend on both the balance of these factors and the facility offered by the state-of-the-art in meeting fabrication requirements. Whatever the balance may be in any specific case, PE devices should eventually widen the all-too-limited present arsenal of electro-mechanical transducers.

THE ELECTRICAL PINCH EFFECT IN INTRINSIC SEMICONDUCTORS

Current Flow in an Anisotropic Semiconductor

Consider an intrinsic anisotropic semiconductor with conductivity and diffusivity tensors $\underline{\sigma}$ and \underline{D} with off-diagonal elements σ_{xy} and D_{xy} . The current density j_x due to an electric field E_x in a rectangular specimen of thickness $2d$ ($-d \leq y \leq d$) is given by

$$\begin{aligned} j_x &= j_{nx} + j_{px} \\ &= \sigma_{xx}E_x + \sigma_{yx}E_y + \frac{e\partial p}{\partial y}(D_{nyx} - D_{pyx}) \end{aligned} \quad (1)$$

with the conventional assumption of quasi-neutrality, so that $\Delta n = \Delta p$, where n and p are electron and hole concentrations, respectively. The electric field E_y results from the open circuit along y ($j_y = 0$):

$$E_y = -\frac{\sigma_{yx}E_x}{\sigma_{yy}} = -\left(\frac{\mu_{nyx} + \mu_{pyx}}{\mu_{nyy} + \mu_{pyy}}\right)E_x \quad (2)$$

where $\underline{\mu} = e\underline{D}/kT$ is the mobility tensor. From Eqs. (1) and (2):

$$\begin{aligned} j_x &= \left(\sigma_{xx} - \frac{\sigma_{yx}^2}{\sigma_{yy}}\right)E_x + kT \frac{\partial p}{\partial y}(\mu_{nyx} - \mu_{pyx}) \\ &= e\mu^*pE_x + kT \frac{\partial p}{\partial y}(\mu_{nyx} - \mu_{pyx}) \end{aligned} \quad (3)$$

where

$$\mu^* \equiv \frac{\mu_{xx}\mu_{yy} - \mu_{xy}^2}{\mu_{yy}} \quad (4)$$

is independent of carrier concentration.

From Eq. (3) it is obvious that there can be a diffusion contribution to j_x from a transverse concentration gradient $\partial p/\partial y$ only as long as $\mu_{nxy} \neq \mu_{pxy}$, i.e., only if the off-diagonal conductivity elements for holes and electrons, σ_{pxy} and σ_{nxy} , are not both zero and not equal to each other.

In addition, from Eq. (3) there is a drift-dependent contribution to j_x which exists only if σ_{xy} , the total off-diagonal conductivity element, does not vanish. It will be shown that it is primarily the diffusive contribution to j_x which causes the large current changes and the other effects associated with the PE.

To determine the total current J_x from Eq. (3), one commences with the equation of continuity:

$$\frac{\partial p}{\partial t} = -\left(\frac{p - p_0}{\tau}\right) - \frac{1}{e} \nabla \cdot j_p \quad (5)$$

where τ is the hole lifetime and

$$\nabla \cdot j_p = \frac{\partial j_{py}}{\partial y} . \quad (6)$$

The hole current, j_{py} , in the transverse direction is given by

$$\begin{aligned} j_{py} &= \frac{-e\partial p}{\partial y} D_{pyy} + peE_x \mu_{pxy} + peE_y \mu_{pyy} \\ &= \frac{-e\partial p}{\partial y} D_{pyy} + \frac{peE_x}{2} (\mu_{pyx} - \mu_{nyx}) . \end{aligned} \quad (7)$$

Finally, from Eqs. (5) and (7)

$$\frac{\partial p}{\partial t} = -\left(\frac{p - p_0}{\tau}\right) + D \frac{\partial^2 p}{\partial y^2} + \left(\frac{\mu_{nyx} - \mu_{pyx}}{2}\right) \frac{\partial p}{\partial y} E_x . \quad (8)$$

Equations (8) and (3) determine the current j_x .

To simplify the above equation it was assumed that

$$\mu_{pxx} = \mu_{nxx} = \mu_{pyy} = \mu_{nyy} .$$

However, the significant conclusions of the subject analysis are not materially affected if this equality does not hold.

From Eq. (3), J_x can now be derived:

$$\begin{aligned} J_x &= \int_{-d}^{+d} j_x(y) dy \\ &= e\mu^* E_x \int p(y) dy + e(D_{nyx} - D_{pyx})[p(d) - p(-d)] . \quad (9) \end{aligned}$$

The spatial distribution of carriers follows from Eq. (8) with the boundary conditions at $y = \pm d$ determined by j_{py} and by the surface recombination velocities $\frac{s_2}{s_1}$:

$$\begin{aligned} j_{py} \Big|_{\pm d} &= -eD \frac{\partial p}{\partial y} + peE_x (\mu_{pyx} - \mu_{nyx}) \Big|_{\pm d} \\ &= \pm e \frac{s_2}{s_1} \Delta p \Big|_{\pm d} . \quad (10) \end{aligned}$$

Equation (10) shows that the transverse carrier concentration $\partial p / \partial y$ depends not only on the surfaces but also on the off-diagonal mobilities μ_{pyx} and μ_{nyx} .

If one assumes a solution of the form:

$$\frac{p(y) - p_i}{p_i} = Ae^{\frac{\alpha_1 y}{L}} + Be^{\frac{\alpha_2 y}{L}} \quad (11)$$

where $L = \sqrt{D\tau}$, the boundary conditions, together with the original continuity equation, yield:

$$\alpha_{1,2} = -\gamma \pm \sqrt{1 + \gamma^2}$$

$$\gamma \equiv \frac{a}{4} \frac{eL}{kT} E_x$$

$$a \equiv \frac{\mu_{nxy} - \mu_{pxy}}{\mu_{yy}} = \frac{D_{nxy} - D_{pxy}}{D_{yy}}$$

$$A = \frac{\gamma}{\xi(\gamma)} \left\{ \left[(s_1 - s_2) \frac{L}{D} + 2\alpha_1 \right] \sinh \frac{\alpha_2 d}{L} - (s_1 + s_2) \frac{L}{D} \cosh \frac{\alpha_2 d}{L} \right\}$$

$$B = \frac{\gamma}{\xi(\gamma)} \left\{ \left[(s_2 - s_1) \frac{L}{D} - 2\alpha_2 \right] \sinh \frac{\alpha_1 d}{L} + (s_1 + s_2) \frac{L}{D} \cosh \frac{\alpha_1 d}{L} \right\}$$

$$\begin{aligned} \xi(\gamma) = & \left[1 + \frac{s_1 s_2 L^2}{D^2} + \frac{\gamma L}{D} (s_1 - s_2) \right] \sinh \left(\frac{2d}{L} \sqrt{1 + p^2} \right) \\ & + \sqrt{1 + \gamma^2} (s_1 + s_2) \frac{L}{D} \cosh \left(\frac{2d}{L} \sqrt{1 + p^2} \right). \end{aligned} \quad (12)$$

Equations (9) and (11) show that the current J_x depends not only on E_x but also on the off-diagonal mobility elements μ_{nyx} and μ_{pyx} and on the free carrier concentration $p(y)$. It will be seen that the elements μ depend on the applied stress and sample orientation, and $p(y)$ depends on the surface recombination velocities and the stress via the mobility elements μ_{nyx} and μ_{pyx} .

To recapitulate in intuitive terms: In an anisotropic semiconductor, a longitudinal field E_x will give rise to a transverse

field E_y if no transverse current j_y is allowed to flow. The field E_y , in turn, induces a drift component of j_x . Similarly, a concentration gradient $\partial p/\partial y$ will give rise to a diffusion current contribution to J_x , provided the off-diagonal diffusivity elements for holes and electrons are unequal. (In isotropic semiconductors, the diagonal diffusivity elements would have to be unequal.) The concentration gradient $\partial p/\partial y$ which contributes to the current j_x is itself dependent on the off-diagonal mobility elements and on the properties of the transverse surfaces.

The Stress-Induced Electric Pinch Effect

In the previous subsection, it was shown that there can be a contribution to the current J_x because of off-diagonal elements of the mobility and conductivity tensors in anisotropic semiconductors. In this subsection, these tensor elements will be related to stress and sample orientation in cubic crystals.

Consider a rectangular sample with axes x, y, z , which do not coincide with the crystal axes x', y', z' .

If (ℓ_1, m_1, n_1) , (ℓ_2, m_2, n_2) , and (ℓ_3, m_3, n_3) are the direction cosines of the sample axes with respect to the crystal axes, then

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} \ell_1 & m_1 & n_1 \\ \ell_2 & m_2 & n_2 \\ \ell_3 & m_3 & n_3 \end{pmatrix} \begin{pmatrix} x' \\ y' \\ z' \end{pmatrix} \quad (13)$$

or, in matrix notation,

$$\underline{x} = \underline{A} \underline{X}' .$$

The piezoresistance $\delta\rho/\rho_i$ may be expressed in terms of the piezoresistance tensor $\underline{\pi}$ and the stress tensor \underline{K} by

$$\frac{\delta\rho_{ij}^{n,p}}{\rho_i} = \sum_{k,\ell} \pi_{ijk\ell}^{n,p} K_{k\ell} \quad (14)$$

or, with stress along the x -axis, by

$$\frac{\delta\rho_{12}}{\rho_i} = \frac{\delta\rho_{xy}}{\rho_i} = \pi_{1211}K_{11} \quad (15)$$

where π_{1211} lies in the sample coordination system. A similarity transformation yields the piezoresistivity tensor in the crystal coordinate system:

$$\frac{\delta\rho_{12}}{\rho_i} = \sum_{p,q,m,n} A_{lm}^{-1} \pi'_{mnpq} A_{pl} K_{11} A_{lq}^{-1} A_{n2} \quad (16)$$

For a cubic material π' can be resolved into three elements and, from Eqs. (13) and (16):

$$\frac{\delta\rho_{12}}{\rho_i} = (\pi'_{11} - \pi'_{12} - \pi'_{44}) (\ell_1^3 \ell_2 + m_1^3 m_2 + n_1^3 n_2) K_{11} \quad (17)$$

The extrema of the second bracket in Eq. (17) are ± 0.281 , corresponding to the following orientation (ref. 2):

$$\begin{pmatrix} \ell_1 & m_1 & n_1 \\ \ell_2 & m_2 & n_2 \\ \ell_3 & m_3 & m_3 \end{pmatrix} = \begin{pmatrix} 0.305 & 0.305 & 0.902 \\ -0.638 & -0.638 & -0.432 \\ 0.707 & -0.707 & 0.0 \end{pmatrix} \quad (18)$$

This optimum orientation for the PE is depicted in Figure 1.

Since $\delta\rho_{ij}/\rho_i = -\delta\sigma_{ij}/\sigma_i$, the coefficient a in Eq. (12) can be expressed by

$$\begin{aligned} a &\equiv \frac{\mu_{nxy} - \mu_{pxy}}{\mu} = -\left(\frac{\delta\rho_{xy}^n}{\rho_i} - \frac{\delta\rho_{xy}^p}{\rho_i} \right) \\ &= 0.281 \left[(\pi'_{11} - \pi'_{12} - \pi'_{44})^p - (\pi'_{11} - \pi'_{12} - \pi'_{44})^n \right] K_{11} \quad (19) \end{aligned}$$

In germanium and silicon (ref. 3):

$$a_{\text{Ge}} = 0.67 \times 10^{-4} (\text{cm}^2/\text{kg}) K_{11}$$

$$a_{\text{Si}} = -0.034 \times 10^{-4} (\text{cm}^2/\text{kg}) K_{11}$$

whence, from Eq. (17):

$$\left. \frac{\delta \sigma_{xy}}{\sigma_i} \right)_{\text{Ge}} = 0.15 \times 10^{-4} (\text{cm}^2/\text{kg}) K_{11}$$

$$\left. \frac{\delta \sigma_{xy}}{\sigma_i} \right)_{\text{Si}} = -0.72 \times 10^{-4} (\text{cm}^2/\text{kg}) K_{11} . \quad (20)$$

With $\delta \sigma_{xy}$ and a given, and from Eqs. (9) and (10) the PE is now fully defined in terms of stress, electric field, recombination velocity, and diffusion length.

Figure 2 shows the experimental current-voltage characteristics, with force K_{11} as a parameter, found by Rashba et al (ref. 1) in germanium. Under pinch conditions dJ_x/dK_{11} is considerably larger than for ordinary piezoresistance; for $E_x = 100$ V/cm and $K_{11} = 10^3$ kg/cm², for example, the current change is two orders of magnitude larger than that produced by piezoresistance in optimally oriented samples. With the two surface recombination velocities unequal, the case treated in Figure 2, the PE is polarity-dependent since the stress-induced concentration gradient of free carriers, depending on the direction of E_x , will either aid or oppose the surface-determined concentration gradient. The non-linearity of the I-V characteristic is a consequence of the complex dependence of free-carrier concentration on stress and electric field through the parameter γ in Eq. (11). The dependence of current on field E_x contains two linear regions, a narrow one for $\gamma \ll 1$ and a more extensive region for $\gamma \gg 1$. Figure 2 shows the linear high field region most clearly in the reverse direction with $K_{11} = 1500$ kg/cm² and $E_x > 30$ V/cm. The current saturation at large fields is probably a result of sample heating.

The dependence of current on stress shown in Figure 3 is complicated at low pressures because of the presence of stress-dependent elements D_{nyx} and D_{pyx} in Eq. (11). The linear high

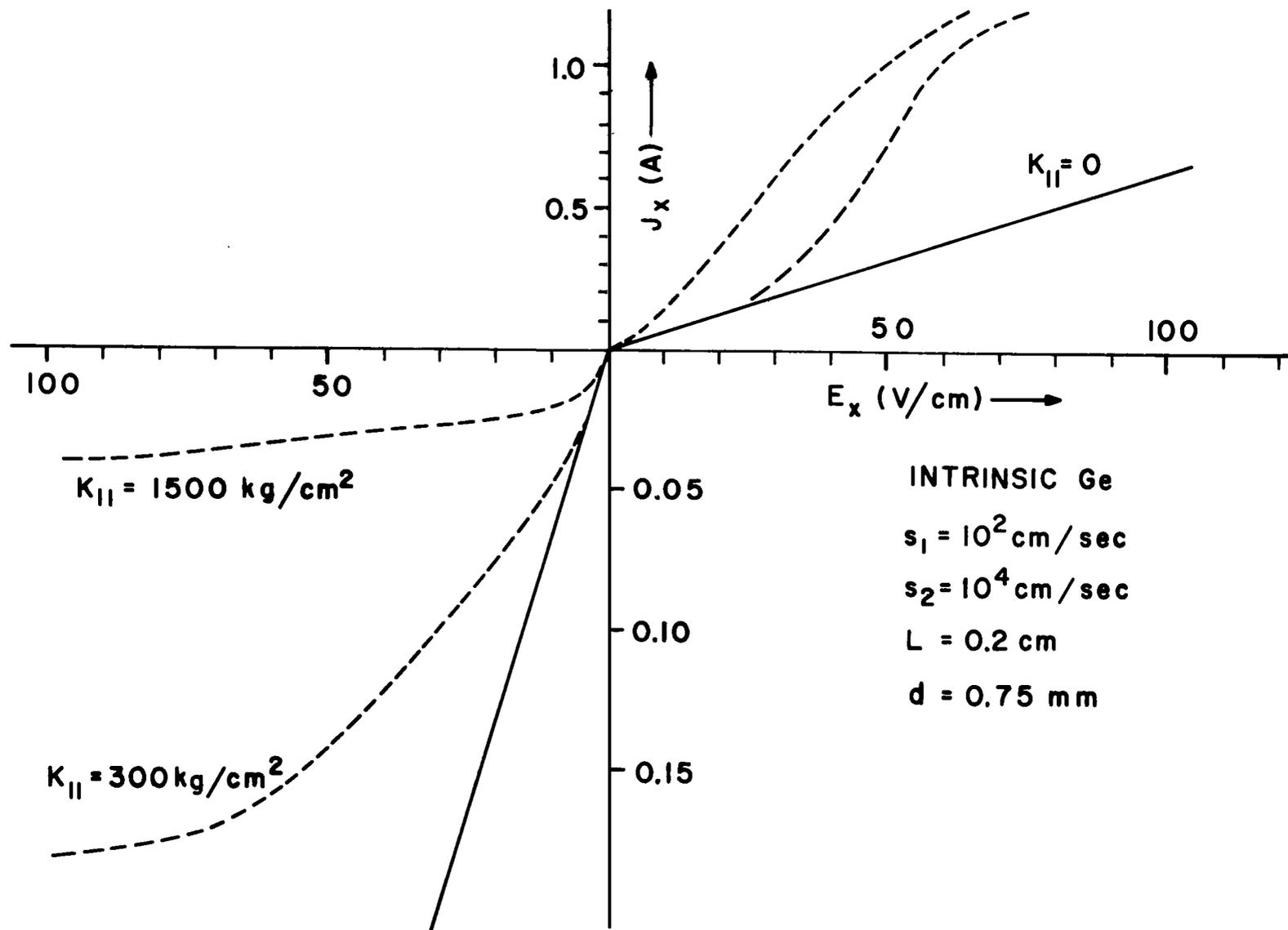


Figure 2.- Current versus electric field for several stresses in a pinched germanium sample (ref. 1).

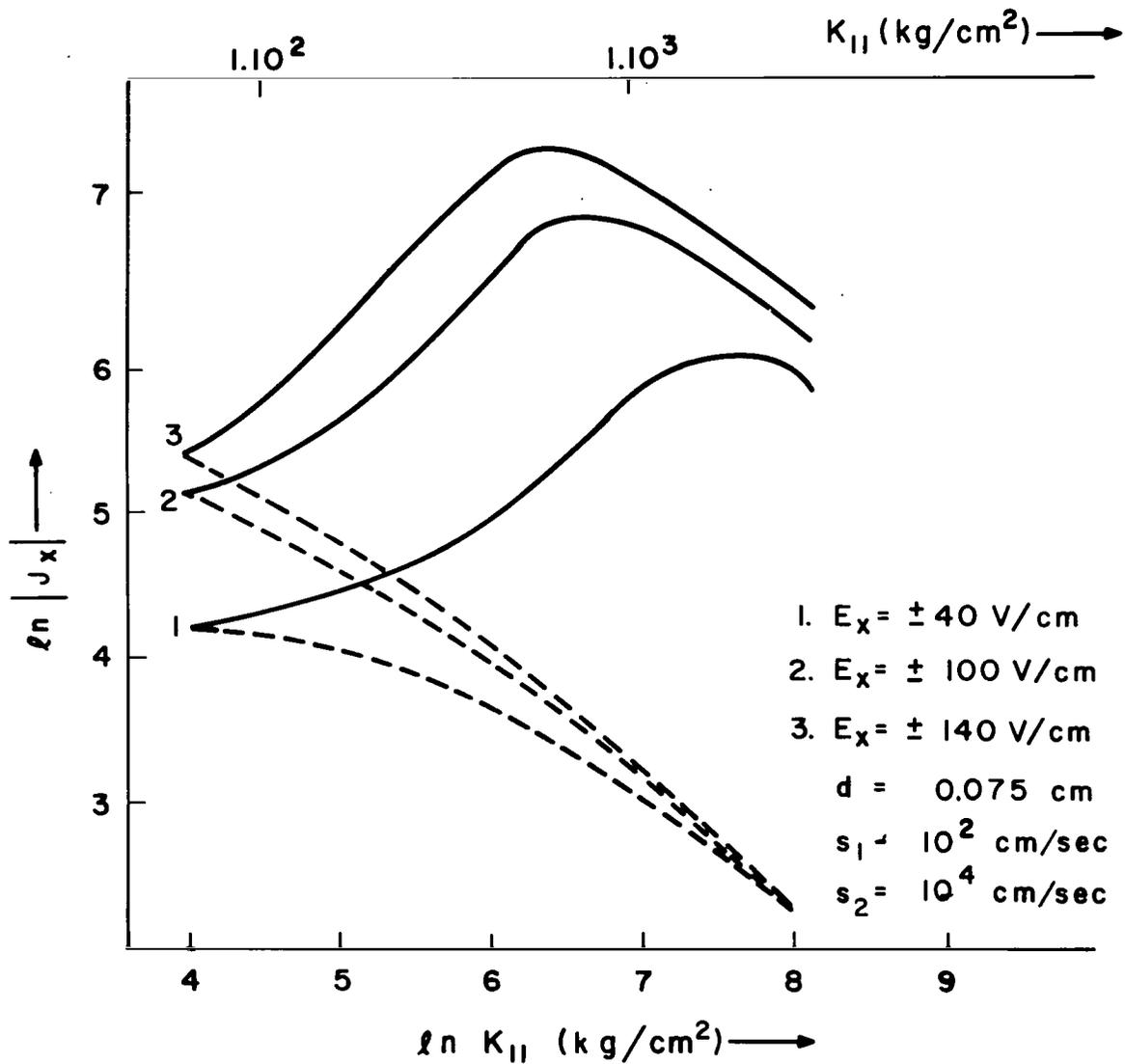


Figure 3.- Current-stress characteristics for a pinched intrinsic germanium sample (ref. 1).

stress region corresponding to $\gamma \gg 1$ lies in the forward direction for $K_{11} > 5 \times 10^2 \text{ kg/cm}^2$ and field $E_x > 40 \text{ V/cm}$, and in the reverse direction for $K_{11} > 10^3 \text{ kg/cm}^2$ and $E_x > 100 \text{ V/cm}$.

The response time of the PE may be derived from Eq. (8). For conditions of strong pinch the last term in Eq. (8) gives the time required to draw carriers across the specimen to the transverse surfaces.

$$\frac{\partial p}{\partial t} = -\left(\frac{p - p_0}{\tau_{\text{eff}}}\right) = \left(\frac{\mu_{nyx} - \mu_{pyx}}{2d}\right) E_x \Delta p \quad (21)$$

so that

$$\tau_{\text{eff}} = \frac{2d}{(aeDE_x)/kT} \cdot \quad (22)$$

For illustration, under a stress of 10^3 kg/cm^2 , the response time is around 5 msec.

The Pinch Effect in Extrinsic Material

For p-type material with $p \gg n$ and with the assumption $D_{nyy} = D_{pyy}$:

$$\begin{aligned} j_y &= \sigma_{yy} E_y + \sigma_{yx} E_x = 0 \\ j_{py} &= e\mu_{pyy} p E_y + e\mu_{pyx} p E_x - eD_{pyy} \frac{\partial p}{\partial y} \\ &= -eD_{pyy} \frac{\partial p}{\partial y} + peE_x \left[\mu_{pyx} - \left(\frac{n\mu_{nyx} + p\mu_{pyx}}{n + p} \right) \right] \\ &\approx -eD_{pyy} \frac{\partial p}{\partial y} - neE_x (\mu_{nyx} - \mu_{pyx}) \end{aligned} \quad (23)$$

$$\begin{aligned} j_x &= \sigma_{xx} E_x + \sigma_{yx} \left[\frac{-\sigma_{yx}}{\sigma_{yy}} \right] E_x + e \frac{\partial p}{\partial y} (D_{nyx} - D_{pyx}) \\ &= epE_x \mu^* + kT \frac{\partial p}{\partial y} (\mu_{nyx} - \mu_{pyx}) \end{aligned} \quad (24)$$

$$j_x = epE_x\mu^* + eaD \frac{\partial p}{\partial y} . \quad (25)$$

The free-carrier concentration can be derived from the equation of continuity:

$$\begin{aligned} \frac{\partial p}{\partial t} &= -\left(\frac{p - p_0}{\tau}\right) - \frac{1}{e} \nabla \cdot j_p \\ &= -\left(\frac{p - p_0}{\tau}\right) + D \frac{\partial^2 p}{\partial y^2} + \frac{eaD}{kT} E_x \frac{\partial p}{\partial y} . \end{aligned} \quad (26)$$

To a first approximation:

$$n = \frac{n_i^2}{p} \approx \frac{n_i^2}{p_0} . \quad (27)$$

The boundary conditions are:

$$-eD_{yy} \frac{\partial p}{\partial y} - \frac{n_i^2}{p_0} \frac{e^2 aD}{kT} E_x = \pm \frac{s_2}{s_1} (p - p_0) \pm d \quad (28)$$

If a solution is now assumed:

$$\frac{p - p_0}{p_0} = Ae^{\frac{\alpha_1 y}{L}} + Be^{\frac{\alpha_2 y}{L}} . \quad (29)$$

These equations can be solved with the same boundary conditions as for intrinsic semiconductors. For clarity, however, the case most favorable for pinch conditions is treated

$$s_1 \rightarrow 0 \quad \text{while} \quad s_2 \rightarrow \infty .$$

Then:

$$Ae^{\frac{\alpha_1 d}{L}} + Be^{\frac{\alpha_2 d}{L}} = 0$$

$$\alpha_1 A e^{-\frac{\alpha_1 d}{L}} + \alpha_2 B e^{-\frac{\alpha_2 d}{L}} = -\frac{n_i^2}{p_0} \frac{eaL}{kT} E_x \quad (30)$$

The solution of Eq. (30) is:

$$A = \frac{-\frac{n_i^2}{p_0} \frac{eaL}{kT} E_x e^{\frac{\alpha_2 - \alpha_1}{L} d}}{\alpha_1 e^{\frac{\alpha_2 - 2\alpha_1}{L} d} - \alpha_2 e^{-\frac{\alpha_2 d}{L}}}$$

$$B = \frac{\frac{n_i^2}{p_0} \frac{eaL}{kT} E_x}{\alpha_1 e^{\frac{\alpha_2 - 2\alpha_1}{L} d} - \alpha_2 e^{-\frac{\alpha_2 d}{L}}} \quad (31)$$

Except for the factor n_i^2/p_0^2 , Eqs. (31) are identical with Eqs. (12) for intrinsic material. If in intrinsic material, A, B, are denoted as A_i, B_i , then:

$$A = A_i \frac{n_o}{p_o}, \quad B = B_i \frac{n_o}{p_o}$$

$$\frac{\Delta p}{p_o} = \frac{n_o}{p_o} A_i e^{\frac{\alpha_1 y}{L}} + \frac{n_o}{p_o} B_i e^{\frac{\alpha_2 y}{L}} \quad (32)$$

For intrinsic material:

$$\Delta p = n_i A_i e^{\frac{\alpha_1 Y}{L}} + n_i B_i e^{\frac{\alpha_2 Y}{L}} . \quad (33)$$

Since the pinch effect depends on Δp , Eq. (33) shows that, for extrinsic material, the absolute change of current with stress is reduced by the ratio

$$\sqrt{n_o/p_o} ,$$

and the relative change of current with stress

$$\frac{\Delta j_x}{j_x} \sim \frac{\Delta p}{p}$$

is reduced by the ratio n_o/p_o , that is, by the ratio of minority to majority carriers.

THE TRANSVERSE PINCH EFFECT

Define a transverse pinch effect (TPE) as a potential along y in response to a field E_x and a stress K_{11} :

$$j_y = e(D_{nyy} - D_{pyy}) \frac{\partial p}{\partial y} + \sigma_{yx} E_x - \sigma_{yy} \frac{\partial v}{\partial y} . \quad (34)$$

The potential difference between the transverse surfaces may be obtained by integration of Eq. (34):

$$V_{+d} - V_{-d} = \frac{D_{nyy} - D_{pyy}}{\mu_{nyy} + \mu_{pyy}} \ln \frac{p(d)}{p(-d)} + 2d \frac{\sigma_{yx}}{\sigma_{yy}} E_x . \quad (35)$$

With both transverse surface recombination velocities greater than about 10^2 cm/sec, the first term in Eq. (35) is one order of magnitude smaller than the second. Thus a transverse

piezoresistive voltage is generated (analogous to that caused by shear in isotropic crystals) which depends on stress, electric field, sample thickness, the piezoresistive coefficients in Eq. (17), and sample orientation.

If one or both surface recombination velocities are smaller than about 10^2 cm/sec, the first term in Eq. (35) dominates, and the TPE is generated by the transverse concentration gradient of free carriers.

CONCLUSION

It has been shown that the LPE is caused by the transverse field E_y and by the effect of stress on carrier concentration and transverse concentration gradient. However, the contribution caused by the field E_y is relatively insignificant; as an example, in silicon (ref. 3), for which $\delta\sigma_{xy}/\sigma_i = .07$, with a stress of 10^3 kg/cm², a field $E_y = .07 E_x$ results which modifies the longitudinal current by only 0.49 percent of the unstressed current.

To recapitulate, the concentration gradient gives rise to a longitudinal diffusion current, provided the off-diagonal diffusivity elements for electrons and holes are not equal. The gradient itself depends on the recombination velocities and on the off-diagonal electron and hole mobility elements; their inequality would imply a net transverse drift current.

The change in total carrier concentration contributes to the longitudinal current through its effect on ordinary drift current, but again depends both on the surfaces and on the mobility elements. In summary, the PE is caused primarily by changes in carrier concentration resulting from stress-induced non-equivalence of off-diagonal mobility elements for electrons and holes. Pictorially, the nature of the effect can be visualized by the plot of carrier concentration vs. transverse position shown in Figure 4 (ref. 1). Under the conditions outlined, carriers and currents are confined mainly to a thin layer along one surface. This "pinched" current is modulated through the dependence on stress of carrier concentration and concentration gradient. The stress dependence of the longitudinal current is generally quite complex as illustrated by Figure 3 which shows an experimentally determined current-stress relation containing both strongly non-linear and quite linear ($K_{11} > 5 \times 10^2$ kg/cm² and $E_x > 40$ V/cm) regions.

It has been pointed out that the PE is maximized if one surface has a very low recombination velocity while the opposite surface has a very high recombination velocity. Values of 10^2 cm/sec and 10^4 cm/sec, respectively, would yield a large LPE; the demands posed in this respect by the TPE are more stringent.

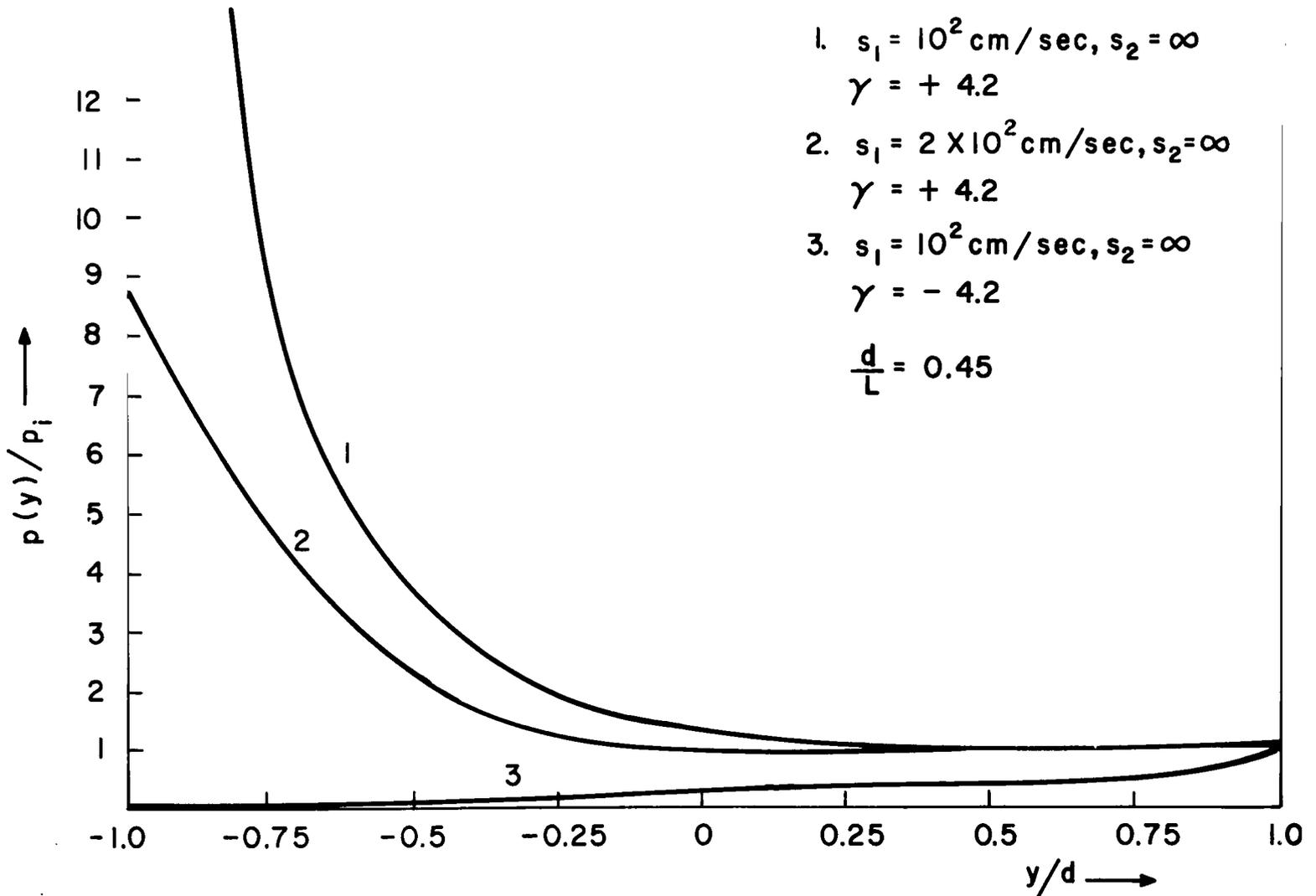


Figure 4.- Transverse distribution of free carriers in pinched germanium for varying surface recombination velocities. Free carriers are confined mainly to one surface if stress and field are in the direction which causes an excess concentration near a low recombination velocity surface (ref. 1).

For the TPE to exceed transverse piezoresistive effects, one surface recombination velocity has to be below 10^2 cm/sec. To convey a feeling for the magnitudes involved, consider an example for

$$s_1 = 10 \text{ cm/sec,}$$

$$s_2 = 10^4 \text{ cm/sec,}$$

$$E_x = 50 \text{ V/cm, and}$$

$$K_{11} = 10^3 \text{ kg/cm}^2 .$$

For this case, the transverse field $E_y \approx 10$ V/cm, somewhat more than transverse piezoresistance would yield under optimal conditions. It must be realized that this value of s_1 is outside the present state-of-the-art for real surfaces; however, the boundary of the pinched current does not necessarily have to be a real surface. It could, for example, be an L-H junction (ref. 4) formed by the boundary between bulk material and a more highly doped region near the surface. Such an L-H junction inhibits flow of excess carriers and thus effectively yields a zero recombination velocity boundary. The feasibility of this or other means of creating the desired boundary will require further study.

Other requirements for generating large pinch effects (both LPE and TPE) include long lifetime and small sample thickness. The semiconductor chosen should be characterized by a large value of the parameter a in Eq. (19). Of the more common semiconductors, germanium best satisfies the latter requirement. The effective response time of the PE is rather long, but adequate for operation in the kHz range; interestingly, the frequency limit goes up linearly with stress.

The temperature dependence of the PE has not been investigated systematically. Besides the effect of temperature on carrier concentration and lifetime, it is expected to arise mainly through the temperature dependence of piezoelectric coefficients in Eq. (19).

In conclusion, the PE offers the potential for transducers of high sensitivity and permits the use of materials not suited for conventional piezoresistive devices. These advantages are obtained at the expense of stringent crystallographic orientation requirements, stringent control of surface recombination velocities, a high frequency response limit in the kHz range, and a

large region of non-linear stress dependence. In view of the obvious complexities of the PE, a realistic appraisal of its device potentialities and limitations will require not only a balance of the factors above, but also further study which will hopefully be stimulated by the present analysis.

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