Thermal Pinching in Electron-Hole Plasma

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A different kind of current pinching than the familiar Bennett pinch effect has been observed in the electron-hole plasma formed in InSb. The new type of pinching is controlled by temperature rather than pressure. It is initiated by the Bennett pinch effect but dominates conduction immediately after the onset of pinching. The necessary critical condition for the onset of this thermal pinch is that the power into the pinch channel less the heat conduction loss be greater than zero. The radii of eight pinch channels have been measured and found to be an order of magnitude smaller than previously thought ($\sim 2\times 10^{-3}$ cm). The density within the pinches exceeds 10^{18} cm^{-3} and the plasma becomes hot enough to cause melting of the lattice within the channel (M.P.$=808$°K).

INTRODUCTION

THE occurrence of current pinching[1] in a solid was first deduced by Glicksman and Steele[2] from conductivity measurements on an electron-hole plasma produced by impact ionization in *n*-InSb. The time required for pinching to occur after the production of the plasma both by impact ionization[3] and injection[4] in InSb has been measured. The critical current required for the onset of pinching was determined by extrapolation to infinite pinch time. These data substituted into Bennett's condition (see later in text) yielded magnitudes for the plasma temperature kT approximately equal to the optical phonon temperature,[5] 0.024 eV. Osipov and Khvoschchev[6] have measured the intensity of recombination radiation across the width (2.6 mm) of an *n*-InSb sample carrying 50 A of plasma current and estimate the radius of the pinch channel ≈ 0.1 mm, the carrier concentration in the pinch $\approx 5\times 10^{16}$ cm^{-3}, and the temperature of the plasma ≈ 500°K (0.043 eV).

The existence of another type of pinch, thermal pinch, was first proposed by Burgess.[7] A semiconductor experiencing increasing power input while immersed in a coolant will heat up preferentially along the axis. This causes enhanced conduction along the axis leading to a concentration of current density there.

In the present work the radius of the pinch channel has been measured, as a function of power into the plasma, and found to be very small, varying only from 1.6×10^{-3} to 4.0×10^{-3} cm. These measurements have led to the experimental recognition of a different kind of pinching than Bennett's, one controlled by temperature rather than pressure. The plasma density within these pinches exceeds 10^{18} cm^{-3} and the plasma becomes hot enough to cause melting of the lattice within the pinch channel.

EXPERIMENTAL

Square cross section, single crystal samples of *p*- and *n*-InSb at 77°K were pulsed with total currents up to 42 A for durations of 1 to 7 μsec with a maximum repetition rate of 1.4 sec^{-1}. (Table I.) The pinch channels so produced left permanent evidence of their existence by disturbing the lattice within the channels. At high plasma power levels the crystals spontaneously cleaved, while undergoing pinch, exposing sections of the column, typically 2–6 mm long, Fig. 1. At low power levels, down to 2 kW/cm, sections of pinch channel were found in every sample in which they were sought by cleaving under the stimulus of ultrasonic vibration. (Two attempts to find channels in *n*-InSb at 1.9 kW/cm were unsuccessful.) The channels are easily observed and measured (error $\approx\pm 3\times 10^{-4}$ cm), Table I, under low-power magnification: They diffuse incident light, whereas the crystal outside the channel reflects it from flat surfaces, i.e., typical cleavage surfaces, Fig. 2. Curved channels have been produced by passing current through side contacts, Fig. 2. The pinch channel boundaries often look "fluted," Fig. 3.

X-ray back-reflection (Laue pattern) photographs have been made of three channels (Nos. 1–3, Table I) and compared with similarly obtained photographs from lattice regions about 0.1 mm outside the pinch boundary. In every case the Laue patterns from outside the channels were typical of "good" single crystal, Fig. 4(a). The Laue spots obtained from within the channels were split into several spots indicating the presence of many dislocation boundaries, Fig. 4(b). This is the type of pattern to be expected from a lattice which had been highly stressed, melted, and then recrystallized in the presence of a "seed" crystal. Channel No. 3 gave more evidence of being polycrystalline than channel No. 1. Channel No. 2 appeared to be very nearly single crystalline.

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[1] W. H. Bennett, Phys. Rev. **45**, 890 (1934).
[2] M. Glicksman and M. C. Steele, Phys. Rev. Letters **2**, 461 (1959); A. G. Chynoweth and A. A. Murray, Phys. Rev. **123**, 515 (1961).
[3] M. Glicksman and R. A. Powlus, Phys. Rev. **121**, 1659 (1961).
[4] B. Ancker-Johnson and R. W. Cohen, Bull. Am. Phys. Soc. **6**, 310 (1961); B. Ancker-Johnson, R. W. Cohen, and M. Glicksman, Phys. Rev. **124**, 1745 (1961).
[5] S. J. Fray, F. A. Johnson, and R. H. Jones, Proc. Phys. Soc. (London) **76**, 939 (1960).
[6] B. D. Osipov and A. N. Khvoschchev, Zh. Eksperim. i Teor. Fiz. **43**, 1179 (1962) [translation: Soviet Phys.—JETP **16**, 833 (1962)].
[7] R. E. Burgess, in *Proceedings of the 1960 International Conference on Semiconductor Physics, Prague* (Academic Press Inc., New York, 1962), p. 818.

TABLE I. Pinch-channel data. Channel No. 8 was formed in n-InSb; the rest were formed in p-InSb.

Channel No.	Area of sample (10^{-3} cm^2)	I_{total} (A)	I_{plasma} (A)	Initial carrier concentration (10^{-14} cm^{-3})	E at onset of pinch (V/cm)	$-\Delta E$ during pulse (V/cm)	Pulse duration (μsec)	Radius of plasma (10^{-3} cm)
1	6.25	31.3	18.2	45	500	17	1.4	1.6
2	6.40	42	40	5.3	450	98	2.5	4.0
3	7.75	42	40	6.2	390	183[a]	4.8	2.5
4	7.75	19	17.3	6.3	360	20[b]	1.5	2.8
5	2.50	11.2	6.0	85	340	92	5.4	3.3
6	2.50	15.5	9.4	92	400	130	6.4	2.5
7	2.50	22	15	90	460	210[c]	7.2	2.5
8	2.50	18	12.7	0.7	400	40	3.8	3.0

[a] Simultaneous decrease in I_{plasma}, $\Delta I_p = -6.0$ A.
[b] $\Delta I_p = -1.0$ A.
[c] $\Delta I_p = -2.0$ A.

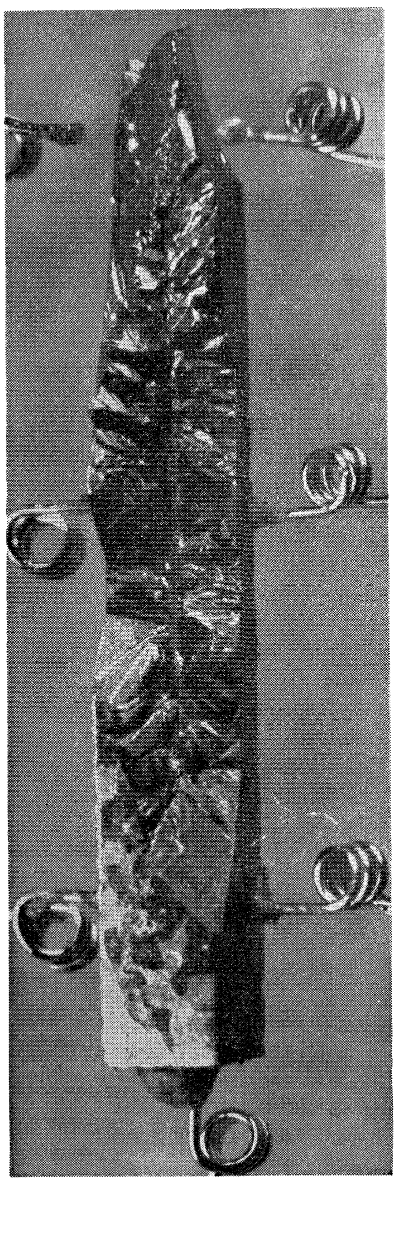


FIG. 1. Example of a pinch channel (No. 1, Table I) exposed by spontaneous cleaving during pinching.

THEORETICAL

The pinches formed typically in 0.05 μsec at which time the balance between magnetic and carrier particle pressure requires a carrier temperature given by Bennett's condition,[1]

$$kT = \mu e P / 4c^2, \tag{1}$$

where k is Boltzmann's constant, T is the common temperature of the carriers, e is the charge on an electron, P is the power input per unit length of plasma, c is the speed of light, and the sum of the electron and hole mobilities is

$$\mu = 7\times 10^8 (T/\text{deg})^{-1.6}\ \text{cm}^2/\text{V-sec}; \quad T > 200°\ \text{K} \tag{2}$$

for indium antimonide.[8] However, the radius of the pinch is not determined by Bennett's theory until the pressure, $2nkT$ (n = electron concentration = hole concentration), is known on the axis. This can be calcu-

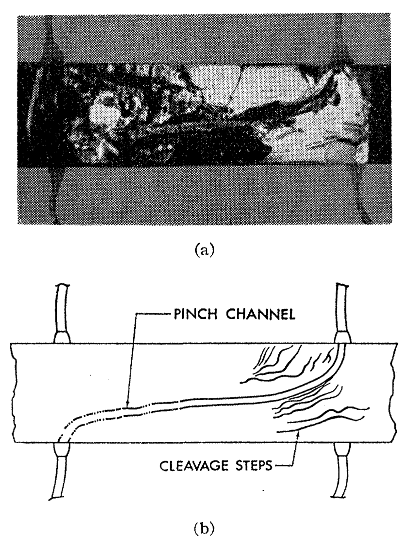


FIG. 2. Example of a pinch channel (No. 4) exposed by mechanically stressing the crystal (not during pinching): (a) photograph; (b) sketch showing cleavage steps and path of current between contacts No. 5 and No. 9. Curvature of the pinch column is clearly visible near contact No. 5 (upper).

[8] C. Hilsum and A. C. Rose-Innes, *Semiconducting 3–5 Compounds* (Pergamon Press, Inc., New York, 1961), p. 126.

lated from the intrinsic electron concentration for indium antimonide,[9]

$$n=4.2\times10^{14}\ (\mathrm{cm})^{-3}(T/\mathrm{deg})^{3/2}e^{-0.125\ \mathrm{eV}/kT}, \quad (3)$$

provided this is greater than the concentration in the pinch of electrons produced by injection and/or impact ionization. The pinch radius (defined by $I=\pi r^2 J$, where J is the maximum current density of the pinch) is given by

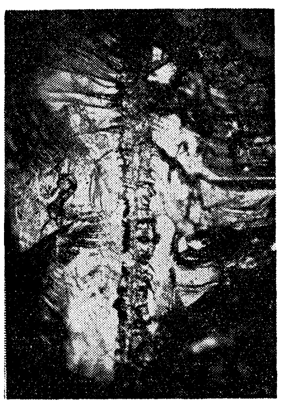
$$r=I(\pi\mu enP)^{-1/2}, \quad (4)$$

where I is the plasma current.

DISCUSSION

Equation (4) is plotted (as the curve marked Bennett's theory) in Fig. 5, making use of Eqs. (1)–(3). The experimental points shown by x's were taken from the data on momentarily stationary pinches near the beginning of the pulses. Within a few hundredths of a μsec after the onset of pinching, the whole pinch column, lattice as well as carriers, rises to the melting temperature of the lattice because the pinch radii are so minute and the net power in the plasma column is so great. The net power is the input power, P, less the conduction loss of heat per unit length per unit time. The latter is

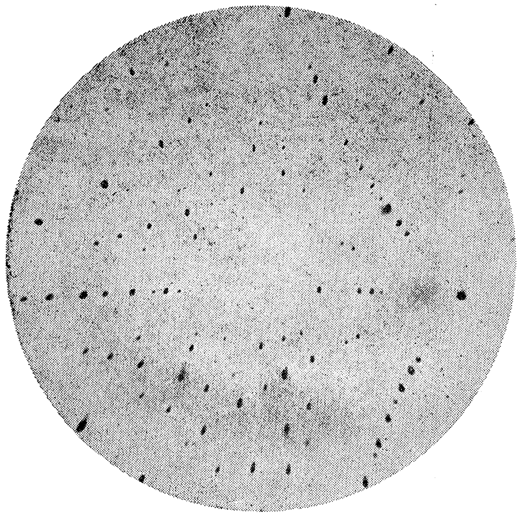
$$H=2\pi r\kappa(dT/dr), \quad (5)$$



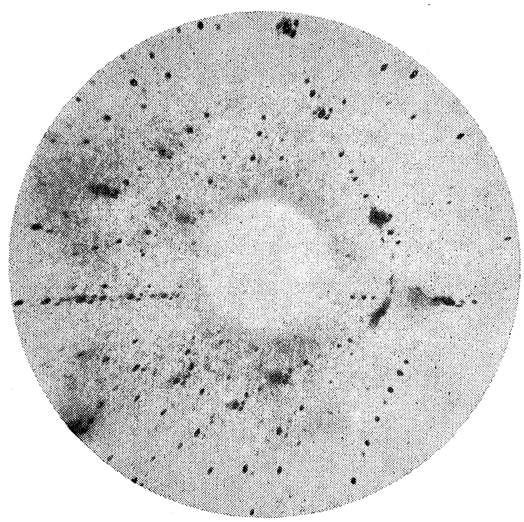
(a)

(b)

FIG. 3. (a) A section of channel shown in Fig. 2; (b) a section of channel shown in Fig. 1 enlarged 400 times to show the "fluted" nature of the boundary.



(a)



(b)

FIG. 4. (a) Laue Pattern obtained from a region of crystal ~0.1 mm outside the pinch channel [compare Fig. 3(b)]; (b) Laue Pattern obtained from a region of crystal within the channel with almost the same orientation between crystal and x-ray beam as in (a).

with κ the thermal conductivity being

$$\kappa=\mathcal{L}/T, \quad (6)$$

where, for indium antimonide,[10]

$$\mathcal{L}=70\ \mathrm{watts/cm}.$$

As an estimate at the pinch radius,

$$dT/dr\approx T/r,$$

so the heat loss per unit length$=0.4$ kW/cm$\ll P$. The lattice begins melting within the column and producing an intrinsic carrier concentration [1.6×10^{18} cm^{-3}; Eq.

[9] G. Busch and E. Steigmeier, Helv. Phys. Acta 34, 1 (1961). This omits effects due to changes in band shape and degeneracy at the highest temperatures, but agrees fairly well with experiments. For a more general expression see H. Ehrenreich, J. Phys. Chem. Solids 2, 131 (1957).

[10] N. H. Nachtrieb and N. Clement, Fluid Phys. Chem. 62, 876 (1958).

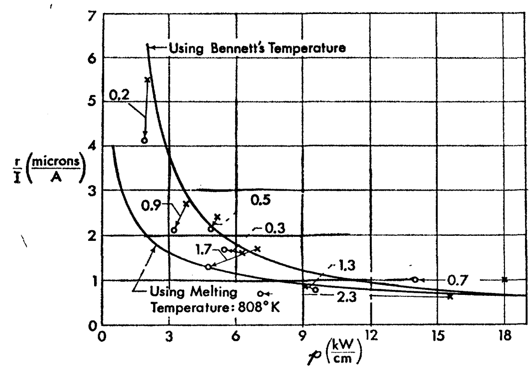
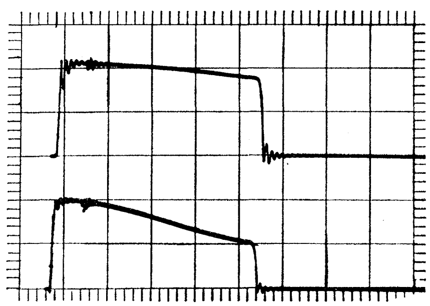
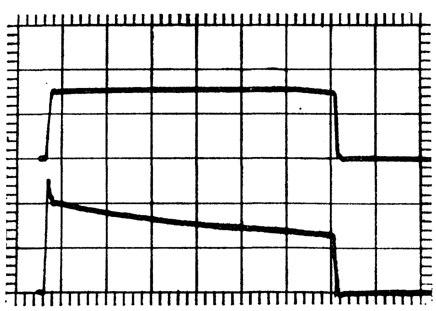


FIG. 5. The pinch radius divided by the plasma current as a function of the power input per unit length of plasma. The crosses represent experimental data at the onset of pinching; the circles, at the end of the pulse. The heavy lines represent the theoretical relationships.

(3)] appropriate to this temperature (808°K). This production of a large number of carriers increases the conduction of the sample so much that the voltage across it (with nearly constant current supplied) drops by a significant percentage during the pulse, as shown by $-\Delta E$ in Table I and Fig. 6. As indicated by the arrows, each of the experimental points on Fig. 5 moves away from the curve determined by Bennett's critical temperature and toward the curve determined by the thermal condition (melting temperature). The approximate net energy given the column, i.e., the net power times the ratio of the pinch duration to the heat of fusion[10] of the crystal within the column, is indicated in Fig. 5, in units of the energy required to melt the column for each measurement. In those cases for which the temperature acquired values much greater than necessary

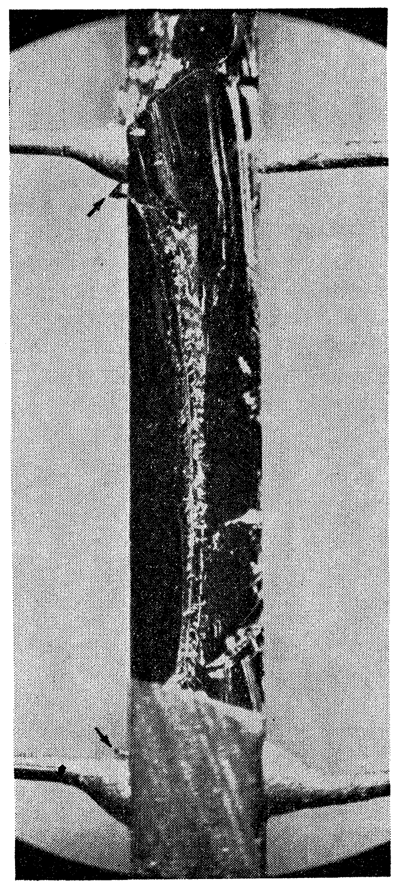


(a)

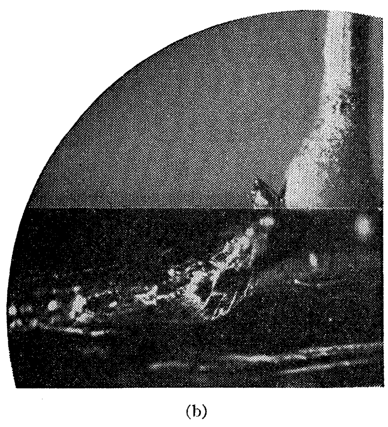


(b)

FIG. 6. Oscilloscope traces: (top) total current through the sample and (bottom) voltage difference between two soldered contacts just previous to spontaneous cleavage of (a) channel No. 3, and (b) channel No. 6. For both the time scale is 1 μsec/large division. The electric field strength decreases (see Table I) with time in both cases (the scale is 50 V/cm). The currents are (a) 42 A with a decrease of 6.0 A by the end of the pulse, and (b) 15.5 A showing no decrease during the pulse.



(a)



(b)

FIG. 7. (a) View of channel No. 8 after spontaneous cleaveage with arrows pointing to "squirted" crystal; (b) enlargement of region near one current contact showing a conically shaped piece of crystal which appeared on the surface of the sample after pinching.

for lattice melting, evidence was seen of molten crystal "squirting" out the channel at the contacts, Fig. 7.

Were the carrier concentrations as low as the estimates given by Osipov and Khvoschchev,[6] who did not take into account thermal ionization, the theoretical curves in Fig. 5 would be moved up the ordinate by a factor of ~ 6. The conclusions to be drawn from the agreement between the theoretical curves and the experimental points is 1) that thermal ionization takes place within the time (~ 0.05 μsec) required for Bennett pinching to occur and 2) that a different kind of pinching or thermoelectric instability has been observed which continually enhances the current flowing in an extremely narrow channel in a semiconductor. This may be contrasted with an equilibrium model[7] in which thermal conduction just balances joule heating. An analog computer study using parameters appropriate to the materials of the present experiments has shown that an equilibrium thermal pinch at these temperatures would have a radius about half the sample radius and at least an order of magnitude larger than those observed. This present thermal pinch effect is initiated by Bennett's pinch effect but dominates the conduction immediately after the onset of pinching and for the entire remainder of the pulse ($\sim 99\%$ of the time). The necessary critical condition for the onset of the instability is that after initiation the power into the pinch less the heat conduction loss be greater than zero.

ACKNOWLEDGMENTS

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Interband Faraday Rotation in Germanium

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The room-temperature Faraday rotation of germanium has been measured in magnetic fields ranging from 0 to 120 kG for a range of photon energies above and below the band-gap energy at $\mathbf{k}=0$. Evidence for the possible influence of exciton transitions is found in both the weak- and strong-field cases. Saturation of the rotation in large fields is observed at photon energies near the zero-field direct band-gap energy. Certain effects of crystal strain are also observed.

I. INTRODUCTION

THE weak-field Faraday rotation in germanium has been measured by Hartmann and Kleman,[1] by Moss and Walton,[2] and more recently by Piller and Patton.[3] The measurements show a reversal in sign and rapid increase in the magnitude of the rotation as the photon energy approaches the energy for direct interband transitions at $\mathbf{k}=0$ ($\hbar\omega<E_g$). Unfortunately, the earlier measurements are of limited precision in this region and also do not extend to energies above the band gap so that the exact form of the rotation in this region is not revealed. Recently, Nishina, Kolodziejczak, and Lax[4] have reported measurements in strong magnetic fields which exhibit structure at photon energies larger than the band gap ($\hbar\omega>E_g$).

Theoretical treatments of the Faraday rotation arising from interband transitions have been given by several authors.[5–8] These treatments are based on a model which involves transitions between Landau levels and do not explicitly account for effects arising from the Coulomb interaction of electrons and holes. Such treatments might be expected to apply at photon energies much less than E_g. At photon energies near E_g, the theoretical work of Elliott[9] and the experimental work of Macfarlane, McLean, Quarrington, and Roberts[10] on germanium have shown that the zero magnetic-field absorption due to direct transitions is significantly modified by exciton effects. Furthermore, in strong magnetic fields the theoretical work of Elliott and Loudon[11] and the experimental work of Edwards and

[1] B. Hartmann and B. Kleman, Arkiv Fysik **18**, 75 (1960).
[2] A. K. Walton and T. S. Moss, Proc. Phys. Soc. (London) **78**, 1393 (1961).
[3] H. Piller and V. A. Patton, Phys. Rev. **129**, 1169 (1963).
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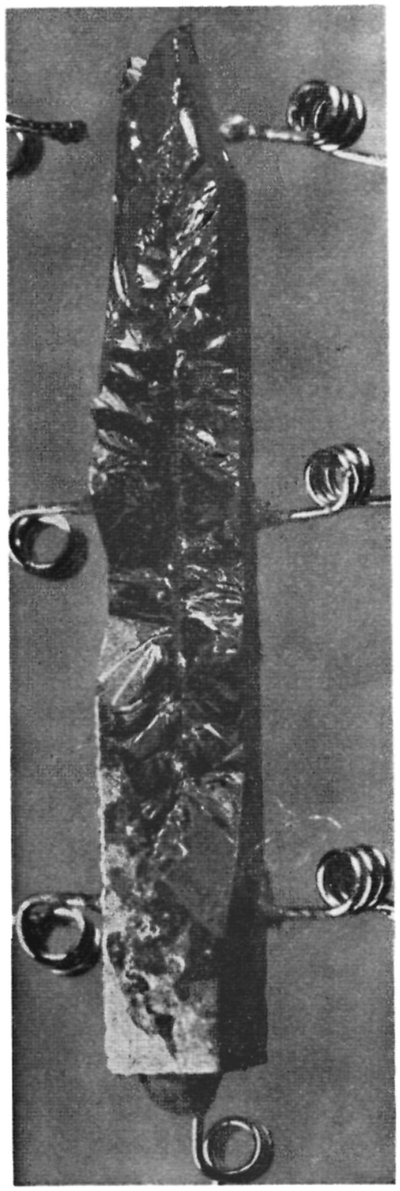


FIG. 1. Example of a pinch channel (No. 1, Table I) exposed by spontaneous cleaving during pinching.

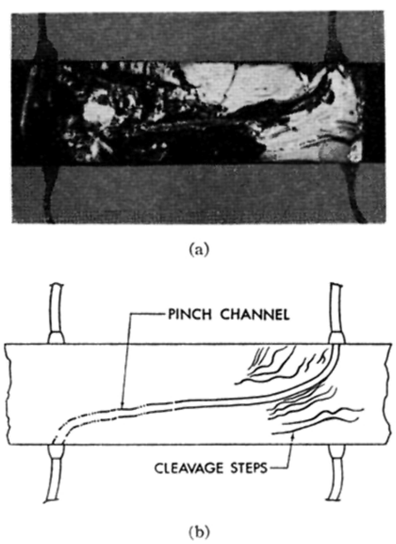
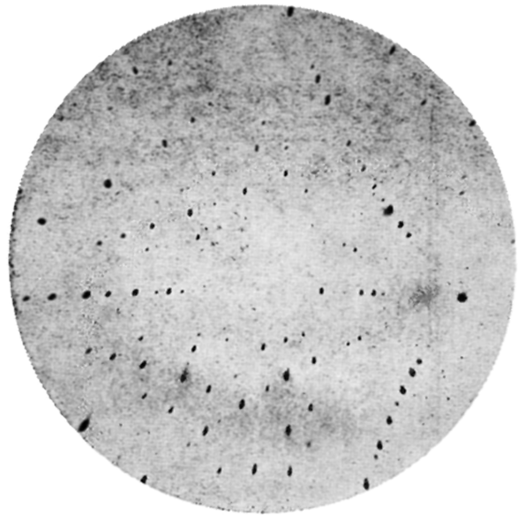


FIG. 2. Example of a pinch channel (No. 4) exposed by mechanically stressing the crystal (not during pinching): (a) photograph; (b) sketch showing cleavage steps and path of current between contacts No. 5 and No. 9. Curvature of the pinch column is clearly visible near contact No. 5 (upper).

(a)

(b)

FIG. 3. (a) A section of channel shown in Fig. 2; (b) a section of channel shown in Fig. 1 enlarged 400 times to show the "fluted" nature of the boundary.



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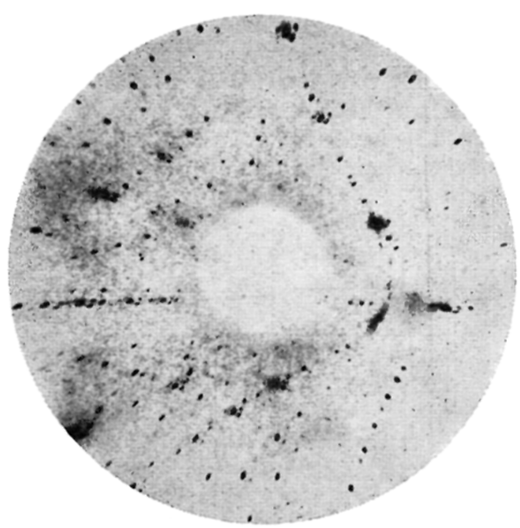
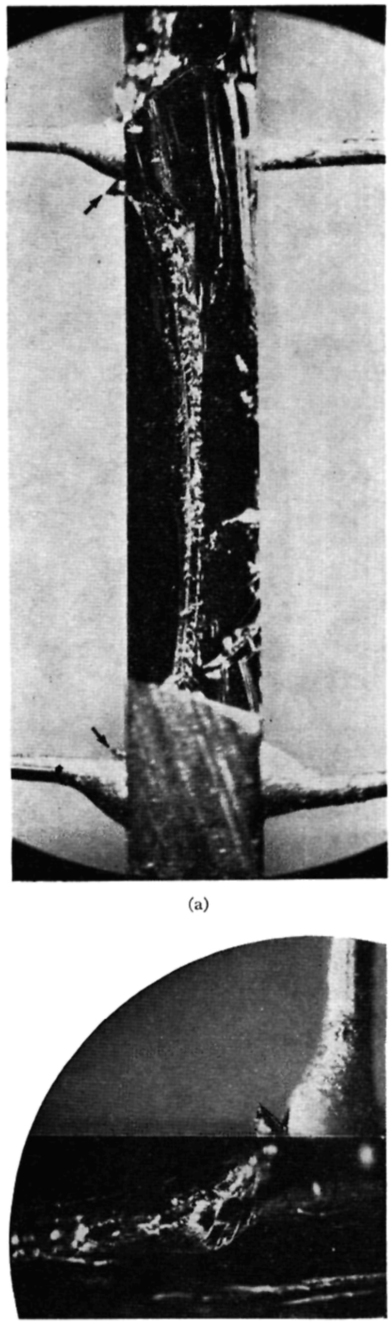


(b)

FIG. 4. (a) Laue Pattern obtained from a region of crystal ~0.1 mm outside the pinch channel [compare Fig. 3(b)]; (b) Laue Pattern obtained from a region of crystal within the channel with almost the same orientation between crystal and x-ray beam as in (a).



(a)

(b)

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