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Drift and Conductivity Mobility in Silicon

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Drift mobility measurements have been made on eleven silicon single crystals ranging in resistivity from 19 to 180 ohm cm. The drift mobility of electrons (μ_n) in the purest *p*-type crystals and of holes (μ_p) in the purest *n*-type crystals can be expressed by the formulas $\mu_n=(2.1\pm0.2)\times10^9T^{-2.5\pm0.1}$ and $\mu_p=(2.3\pm0.1)\times10^9T^{-2.7\pm0.1}$ between 160 and 400°K. At 300°K μ_n and μ_p are 1350 ± 100 and 480 ± 15 cm^2 (volt sec)$^{-1}$, respectively. The conductivity of some of these crystals was measured between 78 and 400°K, and provides independent evidence for the temperature dependences of mobility quoted in the foregoing.

Below 100°K hole mobility in the *n*-type crystals decreases markedly, probably at least in part because of short-time trapping of the injected holes.

BY using a modification of the pulsed field method of Haynes and Shockley,[1] the drift mobility of minority carriers has been measured between 120 and 400°K in high-purity *p*-type silicon crystals and between 78 and 400°K in high-purity *n*-type silicon crystals. For comparison, the conductivity of some of these crystals was measured between 78 and 400°K.

THE EXPERIMENTAL METHOD

The experimental arrangement used to measure drift mobility in *p*-type silicon is shown in Fig. 1. A pulse generator provides a sweeping field of from 0 to 25 volts/cm, lasting for 500 μsec. A second pulse, delayed from the start of the sweeping field, triggers a spark generator[2] and a Tektronix 535 oscilloscope. The spark is focused on the silicon crystal through a slit and produces a short pulse (~several μsec) of minority carriers, which is swept along the crystal by the pulsed field. As the pulse passes the line electrodes *a* and *b*, the simple bridge circuit shown in Fig. 1 becomes unbalanced and then returns to balance. The voltage changes which are displayed on the oscilloscope (see Fig. 2) are a measure of the conductivity modulation produced in the crystal by the pulse of carriers. Temperatures are measured with a thermocouple strapped to the grounded end of the crystal.

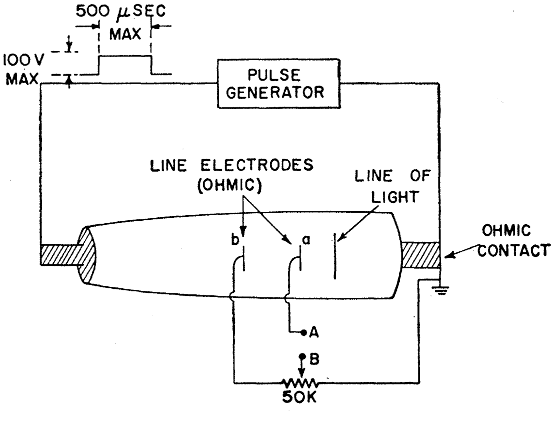

FIG. 1. The experimental arrangement used for the measurement of drift mobility in *p*-type silicon. The pulse of carriers injected with the line of light drifts to the left, toward the positive electrode. The line of light would be moved to the left of contact *b* in measuring drift mobility in *n*-type silicon, since pulses of carriers would drift toward the negative electrode. *A* and *B* are the input terminals of 53D plug-in preamplifier for a Tektronix 535 oscilloscope.

The ohmic contacts to the crystal are made by roughening the etched surface with 150-mesh carborundum (or with a diamond saw in the case of the line electrodes), plating gold on the roughened area, and arcing either indium (for *p*-type crystals) or 97.5% Au 2.5% Sb (for *n*-type crystals) into the plated area.

The drift mobility was calculated from the formula $\mu=d^2/Vt$, where d is the distance between the electrodes (~1 cm), V is the voltage difference between them when the pulsed field is on, and $t=t_b-t_a$ (see Fig. 2) is the time it takes the pulse to travel from one electrode to the other. A small correction (~2%) was applied to the mobility values to take into account the variation in electric field between electrodes *a* and *b*. Other sources of error in μ, such as the change in electric field due to the pulse, the decrease in the measured transit time due to diffusion and recombination while the pulse is passing the electrodes, and the possible inequality of pulse and drift mobilities,[3] were negligible.

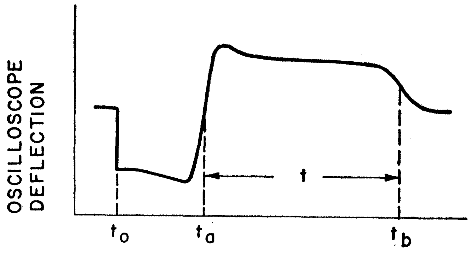

FIG. 2. A typical oscilloscope pattern obtained in the drift mobility experiment. t_o is the time the spark strikes the crystal, t_a is the time the pulse of carriers passes line electrode *a*, and t_b is the time the pulse of carriers passes line electrode *b*.

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[1] J. R. Haynes and W. Shockley, Phys. Rev. **81**, 835 (1951).

[2] The characteristics of the light source, which is also used in lifetime measurements, are discussed by R. L. Watters and G. W. Ludwig, J. Appl. Phys. (to be published).

[3] See M. B. Prince, Phys. Rev. **91**, 271 (1953); W. van Roosbroeck, Phys. Rev. **91**, 282 (1953).

TABLE I. Summary of drift and conductivity mobility results.

Crystal	Type	Doping material	ρ (ohm cm)	μ at 300°K	Exponent of the temperature[a] μ	σ
(1) C-Si-283	p	···	120	1430	−2.5	
(2) E-5	p	···	50	1280	−2.5	−2.7
(3) E-6	p	···	45	1400	−2.5	
(4) RR-159	p	···	45	1420	−2.5	
(5) RR-111	p	···	25	1300	−2.5	
(6) RR-197	p	···	19	1320	−2.3	−2.6
(7) C-Si-170	n	···	180	475	−2.7	−2.5
(8) RR-160	n	P	80	475	−2.7	
(9) RR-158	n	P	45	470	−2.6	−2.5
(10) RR-167	n	P	30	495	−2.6	
(11) RR-168	n	P	19	475	−2.5	

[a] The number given is the power of the temperature which best describes the temperature dependence of the minority carrier mobility as determined by drift (μ column) or of the majority carrier mobility as determined by conductivity (σ column).

CONDUCTIVITY

To find the average conductivity between the line electrodes (on a relative scale), a known current was passed through the crystal and the voltage difference between the line electrodes (~0.1 volt) was measured with a high-impedance voltmeter.[4]

RESULTS

Drift

In five of the six p-type crystals studied, the drift mobility of electrons between 160 and 400°K can be summarized by the formula $\mu_n = (2.1 \pm 0.2) \times 10^9 T^{-2.5 \pm 0.1}$ (see Fig. 3 and Table I). In the sixth and lowest resistivity crystal a slightly different temperature dependence was found ($\mu_n \sim T^{-2.3}$). The electron mobility in several crystals deviates from a power law at lower temperatures.

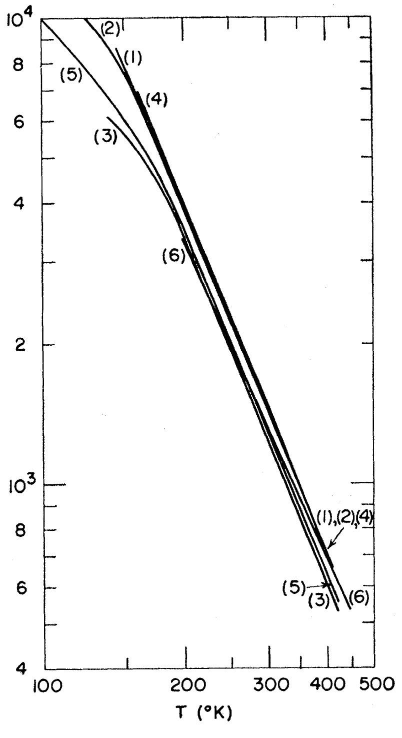

FIG. 3. Drift mobility in some high-purity p-type silicon single crystals.

Between 150 and 400°K, the hole mobility in the n-type crystals behaves like the temperature raised to a power and the exponent which gives the best fit to the experimental data decreases (algebraically) from −2.5 to −2.7 as one proceeds from the lowest to the highest resistivity crystal studied (see Fig. 4 and Table I). At a lower temperature, the value of which increases with decreasing crystal resistivity, the hole mobility passes through a maximum.

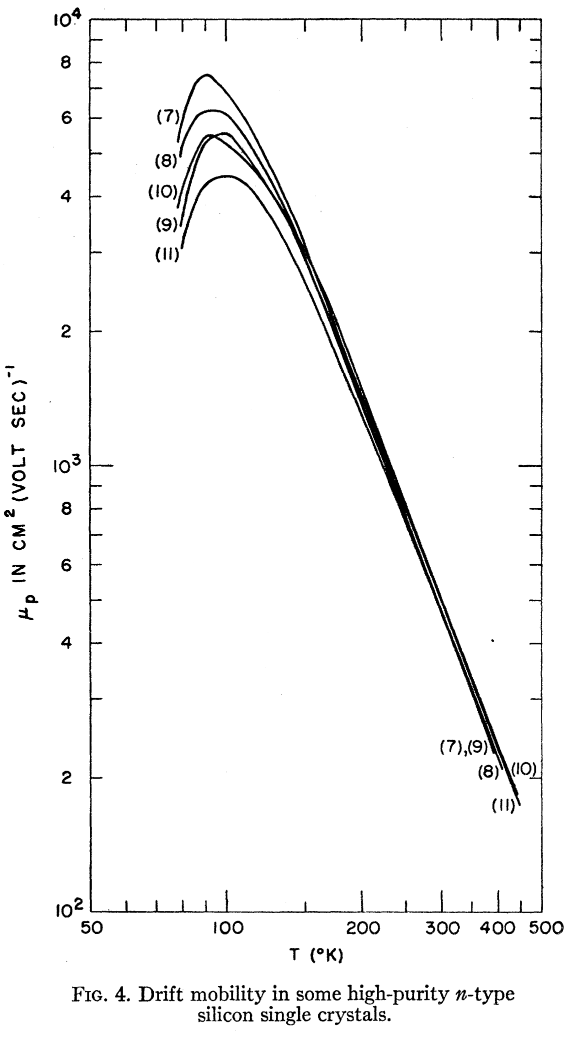

FIG. 4. Drift mobility in some high-purity n-type silicon single crystals.

Between 160 and 400°K the experimental mobility values for a given crystal deviate from the straight line approximation of Fig. 3 or Fig. 4 by at most 10%, while most mobility values fall within 4%.

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[4] A millimicromicroammeter (Scientific Specialties Corporation Model DC-151) was used with the input impedance set at 10^{10} ohms.

Conductivity

The conductivity-temperature measurements on *n*- and *p*-type crystals are summarized in Fig. 5. In this figure the conductivity is scaled to equal the majority carrier mobility at 300°K. The majority carrier mobility at 300°K, in turn, is assumed equal to 1350 in *n*-type crystals and 480 in *p*-type crystals.

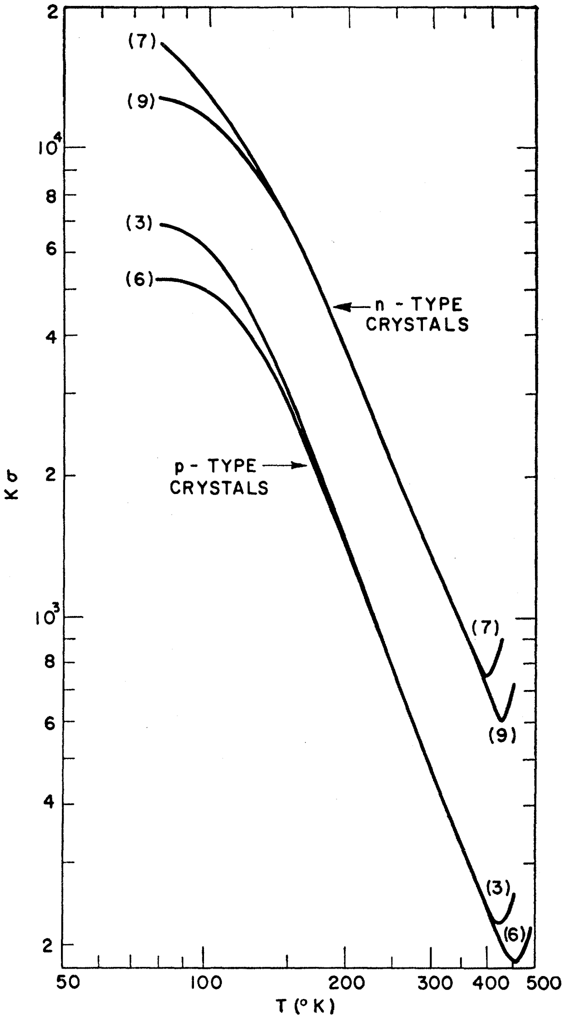

FIG. 5. The variation of conductivity with temperature in some *n*- and *p*-type silicon single crystals. $K\sigma$ is plotted, where K is a constant which converts the conductivity to the majority carrier mobility (as determined by drift experiments on crystals of the opposite type) at 300°K.

DISCUSSION

The drift mobility of holes decreases sharply below 90°K in the *n*-type crystals studied (see Fig. 4). One would expect a slower temperature variation ($\sim T^{+1.5}$) if charged impurity scattering were dominant in this range. It is likely, therefore, that the decrease in mobility is due at least in part to hole trapping.[5] The mobility peak occurs at a higher temperature the lower the resistivity of the crystal, which is consistent with the assumption of trapping, since one might expect as many or more traps in low-resistivity crystals but fewer minority carriers to fill them. Charged impurity scattering would also tend to displace the mobility peak toward higher temperatures in the less-pure crystals. Measurements of hole lifetime[6] in some of these crystals lend independent evidence of trapping at low temperatures. The observed widths of the drift pulses on the oscilloscope screen (which correspond to times ~10 μsec at low temperatures) set an upper limit to the time for which carriers are trapped in a single trapping event.

The mechanisms which bring about the decrease in the hole mobility below 90°K probably influence its temperature dependence above 160°K in the lower resistivity crystals. Hence the formulas $\mu_p = (2.3\pm 0.1)\times 10^9 T^{-2.7\pm 0.1}$ and $\mu_n = (2.1\pm 0.2)\times 10^9 T^{-2.5\pm 0.1}$, derived from inspection of the experimental points for the purer *n*- and *p*-type crystals respectively, probably best represent drift mobility in the lattice-scattering range. For reasons which are not understood, the scatter in the scale of the electron mobility is about twice as large as the authors would estimate the likely experimental error to be.

The graphs of σ *vs* T are linear on a logarithmic scale over a considerable temperature range (see Fig. 5). Presumably, the concentration of majority carriers is constant in this range and the variation in conductivity corresponds to the variation in majority carrier mobility $[\sigma(T) = ne\mu(T)]$. From the conductivity measurements on the highest resistivity *n*- and *p*-type crystals, respectively, one therefore may infer that $\mu_n \sim T^{-2.5}$ and $\mu_p \sim T^{-2.7}$, in complete agreement with the drift results.

While the drift mobilities at 300°K, 1350±100 for electrons and 480±15 for holes, agree reasonably well with earlier measurements of Prince,[7] different temperature dependences were found.[8] The conductivity (and drift) measurements agree with results of Morin and Maita[9] in the case of electrons ($\mu_n \sim T^{-2.6}$) but disagree in the case of holes ($\mu_p \sim T^{-2.3}$).

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[5] A similar explanation for some drift mobility results on germanium has been advanced by R. Lawrence, Phys. Rev. **89**, 1295 (1953).

[6] R. L. Watters and G. W. Ludwig, J. Appl. Phys. (to be published).

[7] M. B. Prince, Phys. Rev. **93**, 1204 (1954).

[8] Prince found $\mu_n \sim T^{-1.5}$ and $\mu_p \sim T^{-2.3}$ as compared to the values $\mu_n \sim T^{-2.5}$ and $\mu_p \sim T^{-2.7}$ reported here. The discrepancy probably is due largely to a difference in purity of the crystals studied.

[9] R. J. Morin and J. P. Maita, Phys. Rev. **96**, 29 (1954).