Measurement of High-Field Carrier Drift Velocities in Silicon by a Time-of-Flight Technique

C. B. NORRIS, JR. AND J. F. GIBBONS

Abstract—In this paper we describe a time-of-flight technique which has been used to measure the drift velocities of carriers in silicon at high electric fields. Carrier velocities are determined absolutely by measuring the transit time of carriers through a region of approximately uniform electric field and known width in a p^+-ν-n^+ diode. The transit time is obtained directly as the duration of the sample current pulse following bombardment of one face of the p^+-ν-n^+ diode with a very short pulse of 10-keV electrons. The ratio of the known sample width to the measured transit time gives the carrier velocity for a particular value of electric field.

The carrier-velocity data thus obtained are absolute, with an accuracy of approximately ±5 percent. Drift-velocity data for carriers in silicon are presented for electric fields between 4 and 40 kV/cm and the present data are compared with those obtained from measurements of current density in bulk samples as a function of electric field.

I. Introduction

ACCURATE measurements of the drift velocities of carriers in a semiconductor at high electric fields are important for predicting the properties of semiconductor devices as well as in investigations of the mechanisms involved in the transport of carriers at high electric fields. Because of this broad importance, experimental determination of the velocity-versus-field relationship for both holes and electrons in silicon have been made by several investigators (see Ryder,[1] Prior,[2] and Davies and Gosling[3]). However, the data presently available in the literature are neither completely consistent nor free from possible objection. In particular, previous workers inferred the velocity-field characteristic from observations of current density as a function of electric field in bulk samples at high electric fields. However, the space-charge distribution and the resulting variation of electric field in these samples under the conditions of measurement are not known. Furthermore, the data of Prior[2] show that at a given field the averaged carrier velocity as deduced from observations of nonohmic currents may change by more than a factor of two as a result of doping in the range where the fraction of impurity atoms is 10^{-6} to 10^{-8}. This observation is inconsistent with the theoretical expectation that the high-field carrier velocity should be determined by the properties of the silicon lattice for such small impurity concentrations.

Manuscript received November 21, 1966. This research was done with the support of the U. S. Army under Contract DA28-043 AMC-004 82(E). C. B. Norris was supported by the National Science Foundation.

The authors are with Stanford University, Stanford, Calif.

[1] E. J. Ryder, *Phys. Rev.* vol. 90, pp. 766, 1953.

[2] A. C. Prior, *J. Phys. Chem. Sol.*, vol 12:2, pp. 175, 1959.

[3] E. A. Davies and D. S. Gosling, *J. Phys. Chem. Sol.*, vol. 23, p. 413, 1962.

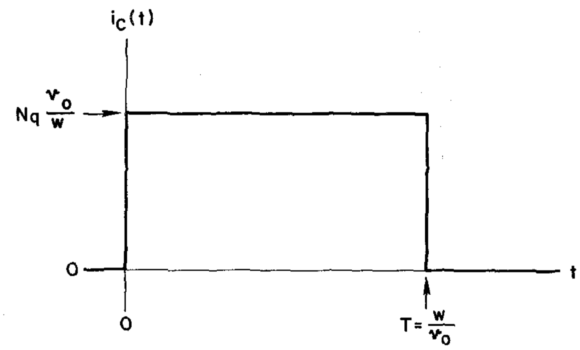

Fig. 1. Average carrier current pulse $i_c(t)$ following injection of N carriers of charge q at one edge of a high-field region of width w. It is assumed that the carriers traverse the depletion region with a constant average velocity ϑ_o.

It is thus desirable to employ a more direct and accurate technique for the determination of high-field carrier drift velocities. In this paper we describe a time-of-flight technique which has been used to obtain accurate and absolute measurements of the high-field drift velocities of carriers in silicon. In this experiment, the carrier velocity is determined by measuring the transit time of carriers through a region of uniform electric field that extends across a sample of known width. Carrier-velocity data for electric fields between 4 and 40 kV/cm are presented and the data is compared to that previously available in the literature.

In the particular arrangement used here, a nearly uniform electric field E is obtained by reverse-biasing a p^+-ν-n^+ diode in which the width w of the ν-region is accurately known. A thin layer of hole-electron pairs is generated near one edge of the diode by bombarding it with a very short (~0.3 ns) pulse of 10-keV electrons. Depending on whether the p^+ or n^+ face of the diode is exposed to the pulsed electron beam, a thin layer of either electrons or holes then traverses the high-field region, producing a current that is ideally like that shown in Fig. 1. A voltage proportional to this current is observed directly on a sampling oscilloscope, from which the field-dependent transit time $T(E)$ is determined. The velocity $\vartheta(E)$ is then obtained as $(E) = w/T(E)$. The accuracy of the velocity data is determined by the accuracy possible in the measurements of sample width and transit time and for the present experiment is approximately ±5 percent.

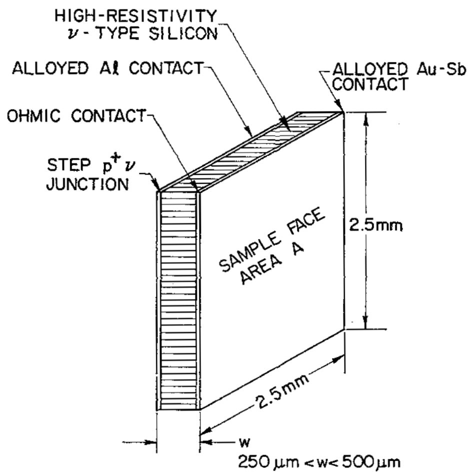

Fig. 2. Samples employed for measurements of carrier velocities in silicon. The depletion region of the $p^+\nu$ junction extends from one contact to the other under relatively low reverse bias. Under typical conditions of measurement the sample bias is such that the electrical field is essentially uniform between the contacts.

II. Sample Structure

The p^+-ν-n^+ diodes were fabricated by alloying contacts, in the form of evaporated thin films of aluminum and gold-antimony (99:1), into opposite faces of a wafer of ν-type (high-resistivity n-type) silicon. The contact evaporation and alloying processes resulted in the formation of step junctions ~100 Å beneath the contact films. The contact film thicknesses were chosen so that a beam of 10-keV electrons would possess substantial energy after passage through the contact film and be able to create electron-hole pairs near one edge of the depletion region of the p^+-ν-n^+ diode.

The ν-silicon used for the samples in all the measurements reported here had a resistivity of approximately 2.3×10^4 ohm-cm and was obtained from Wacker-Chemie. The impurity concentration in this material is $2\times10^{11}/\text{cm}^3$ which permits the ν-silicon between the contact films to be fully depleted under a relatively low reverse bias. Under large reverse bias, the ν-silicon becomes a region of approximately constant electric field. The structure of the samples fabricated for the time-of-flight velocity measurements is shown schematically in Fig. 2. In the following sections, we will consider in detail the pertinent electrical characteristics of the samples and show that these samples will allow the desired velocity determination.

III. Inherent Sample Field Variation and its Effect on Carrier Transit Time

The electric field in the depletion region of a p^+-ν-n^+ diode will vary with distance because of the space charge from both carriers and ionized impurities in the ν-silicon. Ideally, it is desired that the variation in the electric field across the diode depletion region be small compared to the average field so that the ν-silicon may be regarded as a region of approximately constant electric field. In this section we first evaluate the inherent field variation resulting from ionized impurity atoms in the depletion region and then consider the effect of this field variation on the carrier transit time.

Inherent Sample-Field Variation

Assuming that the variation of the electric field E is one-dimensional and that the space charge producing this variation arises from the presence of a constant net density $N_D{}^+$ of ionized donor atoms in the ν-silicon, it follows from integration of Poisson's equation that

$$E(x) = E_0 + E_1\left(\frac{x}{w} - \frac{1}{2}\right) \qquad 0 \le x \le w$$

$$E_1 = \left|\frac{qN_D{}^+}{\epsilon}\right| w. \tag{1}$$

Here q is the value of the electronic charge ($q<0$) and ϵ is the semiconductor dielectric constant. E_1 is the inherent total variation of electric field across the depletion region. As the ν-silicon has a charge density $-qN_D{}^+$ of approximately 3×10^{-8} C/cm³, E_1 is approximately 0.8×10^3 volts/cm for $w=2.5\times10^{-2}$ cm and 1.6×10^3 volts/cm for $w=5\times10^{-2}$ cm. For the majority of measurements reported here the p^+-ν-n^+ diode was reverse-biased to the point where $E_1 \lesssim 0.1\ E_0$, so that under these conditions the field variations inherent in the samples are clearly not of major significance and the ν-silicon is a region of approximately uniform electric field.

Effect of Inherent Sample-Field Variation on Carrier Transit Time

We wish now to show that the electric field variation in the ν-silicon has negligible effect on the measured carrier transit time for all the measurements reported here.

The transit time of a plane of carriers drifting with average velocity $\vartheta_d(E)$ through a region of nonuniform electric field $E(x)$ is

$$T = \int_0^w \{\vartheta_d(E[x])\}^{-1}dx. \tag{2}$$

For the present calculation we assume that $E(x)$ is given by (1) and that we may approximate the actual carrier drift velocity by

$$\vartheta_d(E) = \vartheta_0 \cdot \left(\frac{E}{E_0}\right)^n \tag{3}$$

where ϑ_0, E_0, and n are constants. While ϑ_0 and E_0 are equivalent to one constant in this relation, the use of two symbols will be helpful. E_0 is chosen to be the average electric field in the depletion region and ϑ_0 is the drift velocity when $E=E_0$. With these assumptions we obtain the results

$$\frac{T}{T_u} = \frac{E_0}{E_1}\frac{1}{1-n}\left[\left(1+\frac{1}{2}\frac{E_1}{E_0}\right)^{1-n} - \left(1-\frac{1}{2}\frac{E_1}{E_0}\right)^{1-n}\right] \qquad n \neq 1$$

and

$$\frac{T}{T_u} = \frac{E_0}{E_1}\ln\left[\frac{1+\frac{1}{2}\frac{E_1}{E_0}}{1-\frac{1}{2}\frac{E_1}{E_0}}\right], \qquad n = 1. \tag{4}$$

Here $T_u \triangleq w/\vartheta_0$ is the transit time that would be observed with a uniform electric field, $E(x)=E_0$. We see that, for $n\to 0$, $T\to T_u$ as the velocity is independent of field in this limit.

In the most extreme circumstances employed here, $E_1 \sim 0.4\, E_0$ and $n\sim 1$, we find that $T \cong 1.01\, T_u$. Thus we find that accurate drift-velocity data may be obtained by the present technique in the presence of substantial linear field variations, and that it is quite adequate to consider $T=T_u$ as will be done without further comment in the interpretation of experimental results.

IV. Sample Response to Electron Bombardment: Carrier Currents, Sample Current Waveform, and Carrier Space-Charge Effects

Carrier Currents Resulting from Electron Bombardment

The carrier current can be most simply calculated in circumstances where the electric field is constant in the depletion region. While the field cannot be considered constant under all conditions of measurement, we have shown that field variations do not affect the carrier transit time, which is the quantity of principal interest.

Assuming a constant electric field, it follows that the ensemble average carrier current pulse $i_g(t)$ following generation of a carrier pair at a distance x_g from one edge of the depletion region of width w can be written as

$$i_g(t) = \begin{cases} \dfrac{|q|}{w}(\vartheta_{po}+\vartheta_{no}), & 0 < t < \dfrac{x_g}{\vartheta_{no}} \\[2ex] \dfrac{|q|}{w}\vartheta_{po}, & \dfrac{x_g}{\vartheta_{no}} < t < \dfrac{w-x_g}{\vartheta_{po}} \end{cases} \tag{5}$$

where

ϑ_{p0} = constant drift velocity of holes in the depletion region

ϑ_{n0} = constant drift velocity of electrons in the depletion region.

In this equation we have assumed that $x_g<(w-x_g)$ and that $\boldsymbol{E}$ is in the positive x-direction so that the drift velocity of the electron is in the negative x-direction and that of the hole in the positive x-direction. For $\boldsymbol{E}$ in the negative x-direction, (5) is to be modified by interchanging the subscripts p and n. The average carrier current waveform described by (5) is shown in Fig. 3, from which it may be verified that the total charge collected from one carrier pair generation event is $|q|$.

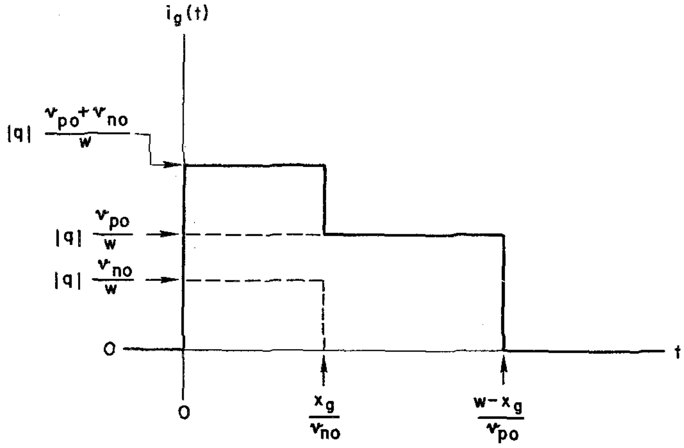

Fig. 3. Average carrier current pulse resulting from a carrier generation event at $x=x_g$. It is assumed that the drift velocities of holes and electrons are constant in the high-field region and equal to ϑ_{po} and ϑ_{no}, respectively. The figure is drawn with $\vartheta_{no}<\vartheta_{po}$ for clarity.

Consideration of (5) further shows that, for a carrier generation event at a location $x_g \ll w$ the fractional charge contributed to the total carrier current pulse by the carrier drifting toward the near contact is approximately x_g/w, independent of the relative magnitudes of carrier drift velocities.

To apply this result to the present situation, where carrier pairs are created in the depletion region by 10-keV electron bombardment, we assume that the carrier pairs are created essentially instantaneously and that the maximum depth of significant carrier pair creation is approximately equal to the practical range x_R of the bombarding electrons. In the present circumstances where we are considering the bombardment of silicon with electrons having energies no greater than 10 keV, we see from the data collected by Dearnaley and Northrop[4] and the work of Viatskin and Makhov[5] that x_R is at most approximately 10^{-4} cm. Since w is greater than 2.5×10^{-2} cm, the creation of carrier pairs by electron bombardment is seen to be indistinguishable from the injection of single carriers at one edge of the sample, and the duration of the carrier current pulse following bombardment of the sample with a short pulse of 10-keV electrons is essentially equal to the transit time of carriers traversing the depletion region.

Relation of Carrier Current to Sample Current

We now consider the relation between the carrier current $i_c(t)$ and the sample voltage when the sample is connected to a reflectionless transmission line of characteristic impedance Z_L. If the diode capacitance may

[4] G. Dearnaley and D. C. Northrop, *Semiconductor Counters for Nuclear Radiations*, p. 10 (Spon. 1964).

[5] A. Ia. Viatskin and A. F. Makhov, *Sov. Phys. Tech. Phys.*, vol. 3, p. 690, 1958.

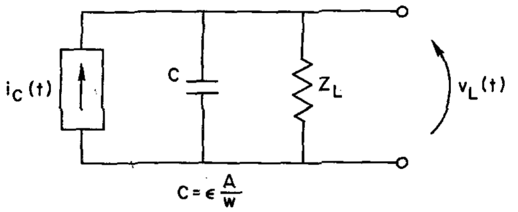

Fig. 4. Relation of carrier current $i_c(t)$ to observable transmission line voltage $v_L(t)$.

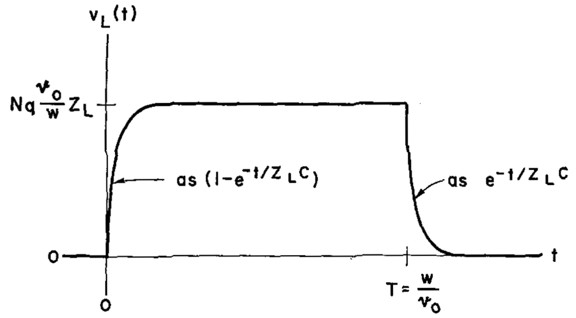

Fig. 5. Transmission line voltage $v_L(t)$ for $i_c(t)$ as shown in Fig 1.

be considered to be a lumped element C, the quantities are related as shown in the equivalent electrical network of Fig. 4. Here the voltage $v_L(t)$ is that launched onto the line from the carrier current in the sample, represented by the current source $i_c(t)$.

For $i_c(t)$ as shown in Fig. 1 we will thus obtain $v_L(t)$ as shown in Fig. 5 for $Z_LC \ll T = w/\vartheta_0$. While it is not necessary that this condition be satisfied for an accurate determination of T from $v_L(t)$, it is desirable to have $Z_LC \lesssim T/25$ so that the approximate shape of $i_c(t)$ may be observed. Thus we desire

$$w \gtrsim 5\sqrt{\epsilon A \vartheta_0 Z_L}, \tag{6}$$

where

ϵ = semiconductor dielectric constant
A = sample area
ϑ_0 = velocity of carriers traversing sample (assumed constant)
Z_L = impedance presented to sample by external environment (assumed resistive).

For square samples (6) can be written in the form:

$$\frac{w}{L} \gtrsim 5\sqrt{\epsilon \vartheta_0 Z_L} \tag{7}$$

where L is the edge dimension of a diode face. For a silicon sample and a line impedance of 50 ohms, the condition becomes approximately

$$\frac{w}{L} \gtrsim \frac{1}{10}. \tag{8}$$

As L is approximately 2.5 mm and w is 0.25 mm or greater, this condition is satisfied.

Pulse Width

To obtain accurate measurements of the carrier transit time with the apparatus available for these experiments it is desirable to have diode current pulse widths of two or more nanoseconds. Since the existing data of Ryder[1] and Prior[2] show that high-field carrier velocities in silicon may have values of approximately 10^7 cm/sec, we see that a sample width of at least

$$w = \vartheta_0 T = 10^7 \frac{\text{cm}}{\text{s}} \cdot 2 \times 10^{-9}\ \text{s} = 2 \times 10^{-2}\ \text{cm}$$

is required to obtain accurate pulse width measurements. The sample widths employed in the measurements reported here were between 2.5×10^{-2} cm and 5×10^{-2} cm, satisfying the condition above.

Carrier Space-Charge Effects

To obtain accurate velocity data by the technique we are considering, we must be able to introduce into the sample a group of carriers with a total charge Q that is sufficiently large to yield a measurable pulse amplitude without significantly disturbing the electric field that existed in the absence of carriers. For the case at hand, where the sample is bombarded over an area of approximately 4 mm² and $\Delta E = 0.25 \times 10^3$ volts/cm is permissible, we can use Gauss's law to show that a total carrier charge $Q \cong 10^{-11}$ C may be introduced into the sample without undesirable effects. The carrier current from this charge is

$$i_c = \frac{Q}{w}\vartheta_0 \tag{9}$$

and, as we are assuming that the sample dimensions and environment are such that the peak sample current is nearly equal to the carrier current, the pulse amplitude available for observation on a transmission line is

$$v_L \cong \frac{Q}{w}\vartheta_0 Z_L. \tag{10}$$

For the most unfavorable circumstances found in the present measurements, namely $\vartheta_0 = 2 \times 10^6$ cm/s and $w = 5 \times 10^{-2}$ cm, we find that $v_L \cong 20 \times 10^{-3}$ volts for a 50-ohm transmission line. This pulse amplitude is readily observable on available sampling oscilloscopes. The transit time of carriers traversing the depletion region may thus be determined with only a small perturbation of the electric field.

V. Experiment

Experimental Apparatus

The experimental apparatus consists basically of a 10-keV electron beam derived from an Eimac 3CX100A5 microwave triode grid-cathode structure and a coaxial sample mount allowing observation of the sample current with one face of the p^+-ν-n^+ diode exposed to the beam. A ring contact to the face of the diode that is exposed to the beam prevents carrier injection near the edges of the sample, so that carrier transport is not influenced by surface properties. The bombarded area is approximately 4×10^{-2} cm^2. To avoid sample heating from surface leakage, reverse bias is applied to the p^+-ν-n^+ diode by 100-μs wide bias pulses synchronized to the beam pulses at a repetition rate of 50 Hz. The basic form of the experimental apparatus is shown in Fig. 6.

To create approximately a plane of carrier pairs in the sample, the grid is modulated by an impulse of voltage obtained from differentiation of a fast-risetime step generated by a mercury-wetted line pulser. The waveform of the modulating voltage applied to the cathode terminal of the microwave triode grid-cathode assembly is shown in Fig. 7. The grid is ac-grounded in this system and the cathode is pulsed negatively to turn on the electron beam. The cathode is biased positively so that the emission threshold corresponds to approximately 20 volts above the maximum negative value of the impulse. This arrangement eliminates the effect of the ringing apparent in Fig. 7 and yields an impulse of voltage with an effective half-amplitude width of approximately 0.2 ns. The cathode is operated under temperature-limited conditions in the velocity measurements. In this situation it is found that the beam current at the sample in response to a step of voltage applied to the grid-cathode structure has a risetime of the order of 0.1 ns, so that the impulse of beam current at the sample will have a half width of the order of 0.3 ns.

Since the carrier transit times are greater than ten times the width of the impulse employed, the thickness of the sheet of carriers created in the sample will be less than $w/10$. This approximation of the ideal situation is quite adequate for the present purposes.

Experimental Data

Carrier velocity determinations from data taken on four samples are reported here. Samples #5, #6, and #7 were fabricated simultaneously from the same piece of material. A typical sample-current waveform following bombardment of the sample with a short pulse of 10-keV electrons is shown in Fig. 8. The carriers in this case are holes. It is seen that the pulse width is a well-defined quantity and that accurate transit-time measurements may be made within the restriction on total carrier charge in the depletion region that assures small space-charge perturbation of the electric field. The transit time is obtained experimentally as the half-amplitude width of the sample current pulse. Since the data of Fig. 9 show that the carrier velocity is not independent of electric field, the flatness of the pulse top in Fig. 8 shows that the carrier velocity and hence the electric field is essentially constant across the depletion region for an $E_0 \sim 10^4$ V/cm.

The time-of-flight drift-velocity data obtained for holes and electrons in silicon are presented in Figs. 9 and

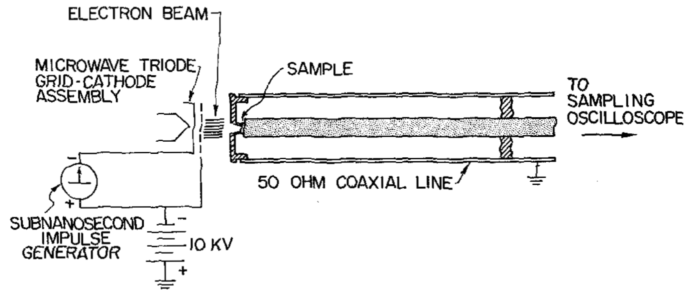

Fig. 6. Basic experimental apparatus employed for time-of-flight measurement of carrier drift velocities.

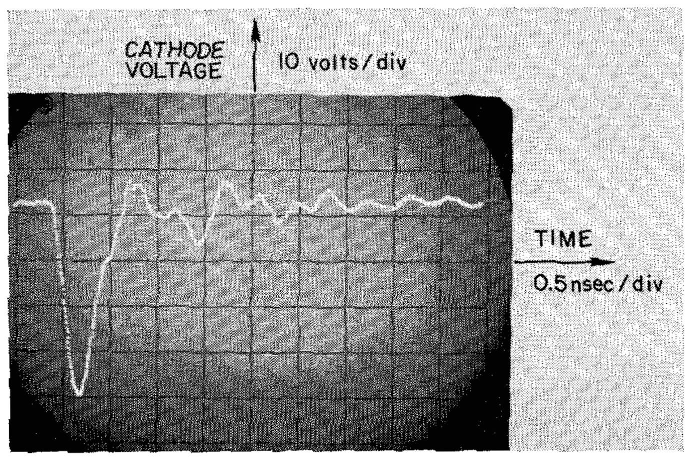

Fig. 7. Impulse of voltage applied to cathode for carrier velocity measurements. The voltage is observed on a 7-ohm coaxial transmission line. The outer conductor of this line is connected to the grid and the center conductor is connected to the cathode.

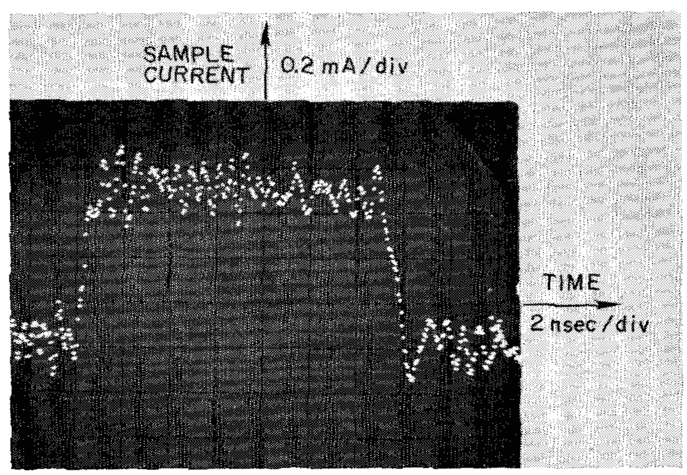

Fig. 8. Typical sample current waveform from holes in Sample #7. The sample thickness is 488 μm and the applied reverse bias is 600 volts. The total carrier charge Q is seen to be approximately 9×10^{-12} C in this measurement.

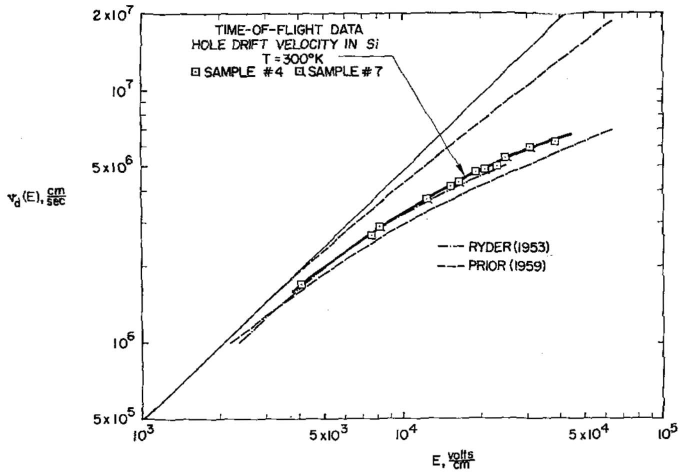

Fig. 9. Drift velocity of holes in silicon as a function of electric field.

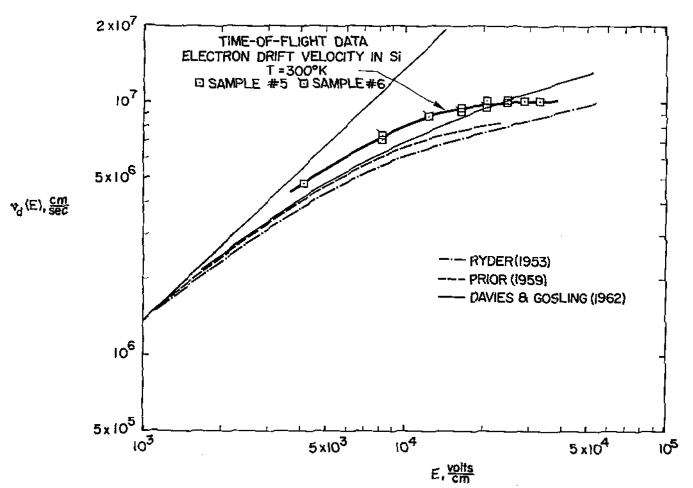

Fig. 10. Drift velocity of electrons in silicon as a function of electric field.

10. Drift-velocity data inferred from the observations of non-ohmic currents carried out by Ryder,[1] Prior,[2] and Davies and Gosling[3] are shown for comparison on these figures. The velocity-field data attributed to these authors were obtained by scaling their current density-field data for bulk silicon samples to obtain low-field mobilities of 480 cm^2/volt-sec for holes and 1350 cm^2/volt-sec for electrons.

The velocity measurements for holes are consistent within experimental error between Samples #4 and #7. These data are seen to agree closely with the data obtained from Ryder and to lie near the lower extreme of the spread obtained from the data of Prior for different sample resistivities.

The velocity data for electrons in Samples #5 and #6 are likewise seen to be consistent well within experimental error. The electron drift velocity in these samples is seen to be greater than that inferred from the data of Prior and Ryder at a given electric field. The tendency for velocity saturation in the time-of-flight data is greater than in the data taken from the work of Prior and that of Davies and Gosling.

The accuracy of the data obtained is determined by the precision that is possible in the measurements of transit time, sample thickness, and sample bias. In the work reported here, it is estimated that the error to be expected in the absolute determination of a velocity is ± 5 percent, and the error to be expected in the determination of the electric field corresponding to that velocity is likewise ± 5 percent. These error limits correspond to squares approximately twice the size of those shown as data points in Figs. 9 and 10.

Acknowledgment

The authors wish to express their gratitude for the comments and suggestions of many reviewers of the manuscript, particularly Dr. M-A. Nicolet and Dr. H. Kroemer.