Lifetimes and Capture Cross Sections in Gold-Doped Silicon

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The free lifetimes of electrons and holes in gold-doped silicon were determined by applying an electric field and measuring the amplitude of the pulses produced by α-particles. Knowing the impurity concentrations and assuming that the lifetime is determined primarily by capture at the gold-sites, the cross sections for capture were calculated. The value for either electrons or holes at neutral gold sites is 2×10^{-15} cm^2 and at oppositely-charged sites, 1×10^{-13} cm^2.

I. INTRODUCTION

THE free lifetimes of carriers in semiconductors have been determined by numerous methods.[1] To relate these measured lifetimes to the capture cross sections of known impurity sites, the density and charge state of these sites must be accurately known and the lifetime must depend primarily upon capture at these sites. At the present state of the art, this implies a doping level greater than 10^{14} atoms/cm^3, and hence, lifetimes considerably less than a microsecond. Lifetimes of this order of magnitude are difficult to measure by conventional methods.

In this investigation, lifetimes of both holes and electrons were determined by employing the semiconductor as a crystal counter and measuring the amplitude of the pulses produced by bombardment with alpha particles. Holes and electrons in equal numbers are produced along a path of about 25 microns by an alpha particle penetrating the surface. By applying a field of the correct polarity perpendicular to this surface, voltage pulses are induced in the electrodes by the motion of either the holes or the electrons. The density of equilibrium carriers must of course not be so great as to mask the effect of the approximately 10^6 carriers produced by the alpha particle. This limits the method to materials having a resistivity greater than about 10^7 ohm-cm. The same method has been employed by others using either alpha particles, light or electron beams, as the source of ionization.[2–4]

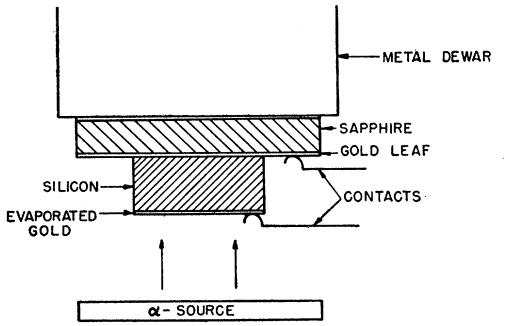

FIG. 1. Arrangement used for determination of lifetimes in silicon using α particles.

The magnitude of the pulse, A, for a crystal thickness, d, (which is large compared to the range of the alpha particle) is given by the equation[5]:

$$A=A_m(\mu\tau E/d)(1-e^{-d/\mu\tau E}), \quad (1)$$

where A_m, the maximum pulse height, corresponds to collection of all the charge. Thus, by measuring A as a function of the electric field, E, the value of $\mu\tau$ may be determined. The mobility μ, can be either estimated or determined by other measurements.

II. EXPERIMENTAL METHOD AND RESULTS

The samples of gold-doped silicon were grown from a doped melt in quartz crucibles.[6] Details of their preparation and properties of these materials have been reported.[7] The impurity concentrations were determined from Hall measurements or from the segregation coefficients and impurity concentrations of the melt during crystal growth.

Most of the samples were prepared by cutting wafers of 5–10 mm^2 area and thicknesses varying from a few tenths of a mm to several mm. They were etched in CP-4 and thin gold electrodes evaporated on the two large faces. Electroplated contacts were difficult to apply because of the high resistance of this material, but appeared to give equivalent results.

A thorough study of the effect of unetched surfaces was not made, but in the few cases that this was tried, no significant variation was observed.

Another geometry that can be used is that obtained by placing a strip of material across the face of the etched crystal and evaporating gold onto this face. By applying voltage across the resulting surface gap and restricting the alpha radiation to only one side of the gap, measurements may be obtained which correspond closely to those obtained by the normal procedure. However, unless the carrier being studied can be made

* Operated by the General Electric Company for the U. S. Atomic Energy Commision.

[1] G. Bemski, Proc. Inst. Radio Engrs. **46**, 996 (1958).

[2] W. Lehfeldt, Nachr. Ges. Wiss. Göttingen **2**, 171 (1935).

[3] K. G. McKay, Phys. Rev. **74**, 1606 (1948).

[4] P. J. Van Heerden, Phys. Rev. **106**, 468 (1957).

[5] K. Hecht, Z. Physik **77**, 235 (1932).

[6] The crystals, together with their impurity concentrations, were supplied by C. B. Collins and R. O. Carlson of the General Electric Research Laboratory.

[7] Collins, Carlson, and Gallagher, Phys. Rev. **105**, 1168 (1957).

to drift a much greater distance than the other carrier, it becomes difficult to separate the contribution of each to the pulse amplitude. Also, for gaps as large as 4 mm, the recombination introduced by unetched surfaces becomes appreciable.

The sample was cemented to a sapphire slab soldered to the end of a metal Dewar as in Fig. 1. A piece of gold leaf was inserted between the sapphire and silicon to make contact with the under surface electrode. In many cases, gold was evaporated only onto the surface exposed to alpha radiation and the gold leaf itself used as the other electrode. This seemed to have no effect on the behavior of the crystal except to perhaps increase the polarization of the crystal due to trapped charges at the boundary.

The radiation used was 5.14-Mev alpha particles from a thin film of sputtered Pu^{239}. The intensity was about 150 alpha/mm^2 sec. Both the samples and alpha source

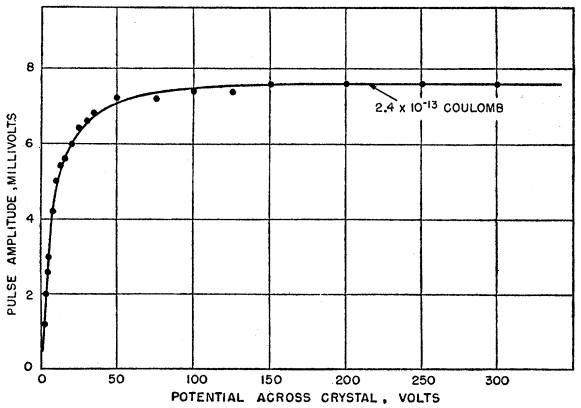

FIG. 2. The amplitude of the integrated current pulses produced by α particles, plotted as a function of the voltage across the crystal Ingot No. 315-3, thickness $d=0.083$ cm; n-type.

were enclosed in a chamber evacuated to about 10^{-5} mm Hg. The integrated current pulses were amplified by a conventional low-noise preamplifier and the amplitude measured on an oscilloscope. For pulse heights approaching the saturation value, very uniform pulses were usually obtained and the pulse height could be estimated to about 2%. For low fields or low lifetimes, in which case the pulse height is only a small fraction of the saturation value, the pulse heights were not as uniform and the average amplitude was estimated to within 10–20%. At liquid nitrogen temperature and low voltages, polarization effects were usually observed which gradually reduced the uniformity and amplitude of the pulses after application of a steady dc field. By raising the temperature to increase the conductivity, this effect usually could be eliminated without greatly increasing the noise level, but equivalent results were obtained by simply measuring the initial pulse heights after application of the field. For properly prepared samples and fields below about 10^4 volts/cm, the noise

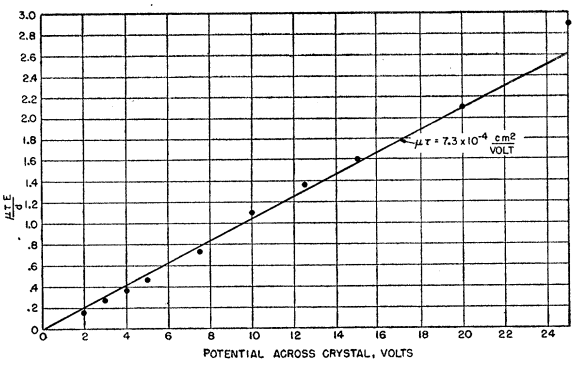

FIG. 3. The value of $\mu\tau E/d$ derived from the pulse-height data of Fig. 2, plotted as a function of the voltage across the crystal.

level of about 20 microvolts was due to the amplifier alone.

Figure 2 shows a typical plot of pulse height as a function of applied voltage showing the close approach to saturation that can be obtained for $\mu\tau$ values of the order of 10^{-4} cm^2/volt.

For obtaining the value of $\mu\tau$ from these data, values of A/A_m are evaluated using either the measured value of A_m or if not attainable, that calculated using 3.60 ev/pair,[8] and the system calibration for known amounts of charge. From Eq. (1), the corresponding values of $\mu\tau E/d$ are obtained and plotted as a function of the applied voltage. The slope of the straight line through these points is $\mu\tau/d^2$. Figure 3 shows the data of Fig. 2 plotted in this fashion. As $\mu\tau E/d$ is very sensitive to small changes in the pulse height near the saturation level, too much weight cannot be given to values of $\mu\tau E/d$ above about 1 or 2.

It is to be expected that for fields above 10^3 volts/cm, the decrease in mobility at high fields would become evident in the pulse-height data. For the longer lifetime carriers, however, the pulse height is insensitive to changes in mobility by the time these high fields are reached. For the low-lifetime carriers, the measured values of $\mu\tau E/d$ in the 10^3 to 10^4 volts/cm range fall increasingly below the values obtained by extrapolating the low-field values. Although the lack of precision in these measurements together with differences in doping and temperature make difficult any comparison with the available data on high-field mobilities in silicon,[9] the deviations noted were approximately those to be expected.

Table I lists the significant properties of the four samples of gold-doped silicon that were studied. The mobility values that are not in parentheses were obtained by measuring the rise time of the nearly-saturated pulses on a wide-band-width oscilloscope. As this results in a rise time of the order of 10^{-8} sec, the accuracy of these measurements is low—about $\pm 20\%$. The values, however, showed good agreement with the calculated

[8] W. D. Davis, J. Appl. Phys. **29**, 231 (1958).
[9] E. J. Ryder, Phys. Rev. **90**, 776 (1953).

TABLE I. Properties of gold-doped silicon at 77°K.

Ingot number and section	Type	Mobility (cm^2/volt sec)	Capture site and density (cm^{-3})		Mean life (sec)	Cross section (cm^2)
			Electrons			
309-7	n	(5.5×10^3)	Au^0,	15×10^{14}	2.7×10^{-8}	2×10^{-15}
309-3	n	6×10^3	Au^0,	5×10^{14}	7×10^{-8}	2×10^{-15}
315-3	n	10×10^3	Au^0,	4×10^{14}	7.3×10^{-8}	3×10^{-15}
308-4	p	(6×10^3)	Au^+,	2×10^{14}	5.9×10^{-9}	0.6×10^{-13}
			Holes			
309-7	n	2×10^3	Au^-,	5×10^{14}	1.3×10^{-9}	1.5×10^{-13}
309-3	n	(2×10^3)	Au^-,	2×10^{14}	7×10^{-9}	0.7×10^{-13}
315-3	n	2.5×10^3	Au^-,	$<10^{14}$	2.4×10^{-8}	$>0.4\times10^{-13}$
308-4	p	2×10^3	Au^0,	6×10^{14}	6.0×10^{-8}	3×10^{-15}

TABLE II. Measured values of mobility×lifetime in gold-doped silicon.

Ingot number and section	Thickness (cm)	$(\mu\tau)_n$ (cm^2/volt)	$(\mu\tau)_p$ (cm^2/volt)
309-7	0.41	1.4×10^{-4}	
309-7	0.087	1.6×10^{-4}	2.6×10^{-6}
309-7	0.041		2.6×10^{-6}
309-3	0.035	3.2×10^{-4}	0.8×10^{-5}
309-3	0.117	6.6×10^{-4}	1.9×10^{-5}
309-3	0.058	3.1×10^{-4}	
315-3	0.083	7.3×10^{-4}	6.0×10^{-5}
308-4	0.041	3.4×10^{-5}	1.3×10^{-4}
308-4	0.124	3.7×10^{-5}	1.1×10^{-4}

mobilities based on the density of charged impurity centers.[10] The values in parentheses were not measured, but are estimated values based on a comparison of the calculated and observed values for the other samples.

Table II lists the measured values of $\mu\tau$ for different thicknesses. Except for ingot 309-3, good agreement was obtained for duplicate samples of different thicknesses. The reason for the poor results from 309-3 is not known, but it appears to lie in the crystal itself rather than in any error in measurement. The pulses exhibited unusual changes in amplitude with time and rate of alpha bombardment which were not observed in the other crystals. (Gold-doped and nickel-doped germanium show similar effects and give $\mu\tau$ values which increase with crystal thickness.) For this reason, the values of $\mu\tau$ for 309-3 can be considered only approximate and may differ from the true value by as much as a factor of 2.

No detailed study was made of the variation of $\mu\tau$ with temperature because the temperature may be increased to only about 170°K before the increased noise makes even rough measurements impossible. In the few cases studied, however, no great variation was noticed. For holes in p-type material or electrons in n-type (capture at neutral sites), the $\mu\tau$ values decreased about a factor of 2–4 as the temperature increased from 77°K to 170°K. As this is the expected decrease in mobility, the lifetime must be approximately constant in this temperature range. Holes in n-type material exhibited a similar behavior, but for electrons in the p-type crystal, the value for $\mu\tau$ increased about a factor of two.

The lifetimes shown in Table I were obtained from the average value of $\mu\tau$ and the measured or estimated value for the mobility.

For calculating the cross section, it was assumed that capture was due solely to the added deep-level impurities and that once captured, the carrier made no further contribution to the pulse of conductivity. It was also assumed that the capture cross section associated with carriers and sites of unlike charge was much greater than that for neutral sites; and the cross section for neutral sites was greater than that for carriers and sites with charge of the same sign. This last assumption is based not only on the repulsion of like charges, but also on the fact that no stable doubly-charged states for gold in silicon are known.[7]

At liquid nitrogen temperature, essentially all the free carriers which, in the absence of the gold, would normally be present are "frozen out." Thus, the density of charged gold sites is taken to be equal to the density of net shallow donors or acceptors, as the case may be. The density of neutral gold sites is then simply the excess of gold over that needed for compensation. These values are listed in Table I.

The average thermal velocity of electrons and holes used in calculating the cross section was 1.3×10^7 cm/sec and 1.0×10^7 cm/sec, respectively.

III. CONCLUSIONS

The cross sections so obtained show reasonably good agreement between samples. There is no apparent difference between holes and electrons at either neutral sites or oppositely-charged sites, the cross sections being approximately 2×10^{-15} cm^2 and 1×10^{-13} cm^2, respectively, for the two types of sites.

For charged sites, Bemski[1,11] obtained cross sections near room temperature which, when extrapolated to 77°K, give a value of 2×10^{-13} cm^2 for holes at Au^- and 1×10^{-13} cm^2 for electrons at Au^+. These values agree quite well with those obtained in this study. For neutral sites, Bemski obtained values of 5×10^{-16} cm^2 and $\geqslant10^{-16}$ cm^2 for electrons and holes, respectively. No dependence on temperature was observed, but his measurements do not preclude a small temperature dependence of the order of T^{-1}.

ACKNOWLEDGMENTS

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[10] E. M. Conwell, Proc. Inst. Radio Engrs. **40**, 1330 (1952).

[11] G. Bemski, Phys. Rev. **111**, 1515 (1958).