Eur. J. Phys. 8 (1987) 34–40. Printed in the UK

A simple and instructive version of the Haynes–Shockley experiment

A Sconza and G Torzo

Dipartimento di Fisica dell'Università di Padova and Gruppo Nazionale Struttura della Materia, via Marzolo 8, 35131 Padova, Italy

Received 7 May 1986

Abstract The Haynes–Shockley technique for the measurement of electron and hole drift mobility μ in semiconductors is here presented in a version suitable for an undergraduate laboratory course. The experiment allows also a quantitative test of the Einstein relation $eD = \mu k_B T$, and it requires only a germanium crystal sample, an oscilloscope and low-cost electronic components.

Riassunto Si descrive una versione dell'esperimento di Haynes–Shockley per la misura della mobilità di deriva μ di buche ed elettroni in semiconduttori, concepita per un laboratorio didattico per laurea in fisica. Questo esperimento permette anche una verifica quantitativa della legge di Einstein $eD = \mu k_B T$, e richiede solo l'uso di un cristallo di Ge, di un oscilloscopio e di componenti elettronici a basso costo.

1. Introduction

The measurement of the electron and hole drift velocity in a semiconductor crystal with a time-of-flight technique was first performed by Haynes and Shockley (1949), and it soon became a standard method in investigations of semiconductors. This experiment should be a basic one in an introductory solid-state laboratory course because it gives a direct and instructive picture of the excess carrier behaviour, demonstrating the basic features of the transistor. No simple and effective arrangement, however, which appears suitable for a standard teaching laboratory, has been suggested in the literature†.

In this article we give therefore some hints to the teacher who wishes to perform this experiment avoiding the use of expensive equipment, and we show that in our set-up the only extra cost, with respect to standard apparatus is due to the semiconductor crystals.

2. The Haynes–Shockley experiment in brief

A p-doped semiconductor bar has two ohmic contacts soldered at the ends (a metal–semiconductor contact is ohmic when its resistance does not depend on either the current intensity or the voltage polarity). A negative voltage generator produces a constant 'sweep' electric field E_s across the crystal for a time of the order of a fraction of a millisecond. Two metallic point probes, separated by a distance d, are placed in contact with the sample on one side. A metal point probe acts as a partially rectifying contact, and it is therefore depicted in figure 1 as a diode (see for instance Walsh 1962).

If a short (~ 1 μs) negative voltage pulse is applied to the probe E (emitter) with an amplitude sufficient to forward bias the diode D_e, then excess electrons are injected into the crystal.

The sweep field E_s forces the electrons to drift with a velocity v, and after a time delay t_0, they will reach the crystal region underneath the probe C. The diode D_c, which is reverse biased, acts as a collector of minority carriers (electrons), and therefore normally only a weak current is flowing through the resistance R. When the excess electrons reach the collector region this current suddenly increases owing to the larger minority-carrier density, and therefore a negative pulse across R is detected by the oscilloscope.

Actually two peaks appear at the collector for each injected pulse. The first one has amplitude and width comparable to that of the signal externally applied to the emitter: it is due to the electromagnetic field signal

† Suitable experimental apparatus can be obtained commercially, e.g. in the UK from Research Instruments Ltd, Kernick Road, Penryn, Cornwall.

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that travels from the emitter to the collector practically at the speed of light (and therefore with negligible delay). The second one is the signal due to the excess minority carriers flowing past the collector: it is much smaller and broader than the first pulse, owing to recombination and diffusion processes. The separation of the two peaks on the oscilloscope time scale yields the minority carrier time of flight t_0.

The drift velocity is then obtained as $v=d/t_0$ and the mobility as $\mu=v/E_s$. Assuming a negligible resistance for the end contacts, the sweep field is simply $E_s=V_s/l$, where V_s is the applied sweep voltage and l is the sample length. The mobility is therefore measured as $\mu=dl/(V_s t_0)$.

Information on the diffusion and recombination of the excess carriers can be obtained by measuring the width and the area of the collected pulse, as will be shown in § 4. By using an n-doped crystal and positive sweep and injecting voltages, one can similarly measure the hole drift mobility. In this case the polarities of the diodes D_e and D_c are both reversed.

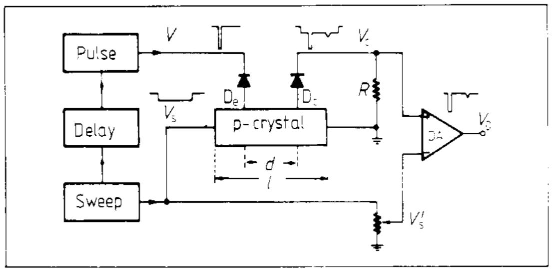


Figure 1 Block diagram of the experiment: D_e and D_c are the emitter and collector point probe contacts and DA is the differential amplifier.

3. Experimental apparatus

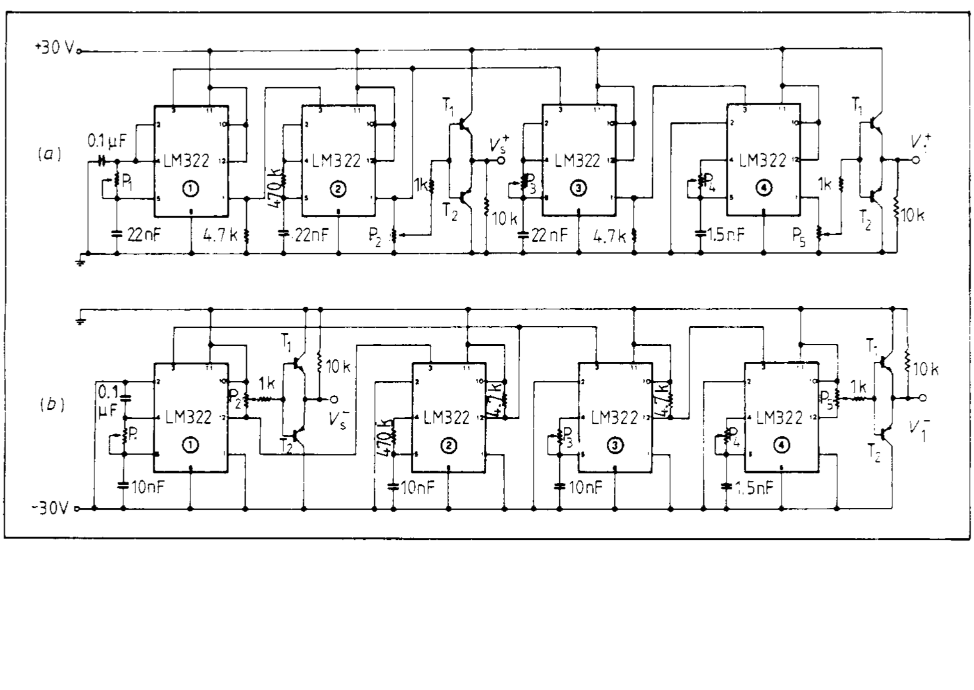
The block diagram of the apparatus is shown in figure 1. The sweep field cannot be constantly applied to the sample, otherwise Joule heating would affect the measured mobility which is temperature dependent. Therefore a low-duty-cycle pulser, with adjustable output voltage, must be used. A convenient repetition rate can be of the order of several hundred Hertz.

The injecting pulse has to be triggered by the sweep signal after a suitable delay, in order to avoid the signal distortion during the V_s switch-on transient. The duration of this pulse must be as short as possible (e.g. 1 μs) and its amplitude must be also adjustable. A very simple circuit that provides both the sweep and the injecting pulses with all the required features, is shown in figure 2(*a*) (positive pulses to measure the hole mobility) and in figure 2(*b*) (negative pulses for electron mobility).

Only four integrated circuits (National LM 322 IC-timer) are required to provide the desired functions. The sweep signal is produced by an astable multivibrator (IC 1 and IC 2), with adjustable frequency and duty cycle. The variable delay is provided by a first monostable (IC 3) and the injecting pulse is generated by a second monostable (IC 4). The sweep and the injecting pulses are boosted by a current amplifier stage (T_1 and T_2) which also provides the amplitude control.

The power supply required by these circuits may be either a dual unit ($\pm$ 30 V) referred to the common

Figure 2 The double pulser circuit: (*a*) negative output for electron injection and sweep in p-doped samples; (*b*) positive output for hole injection in n-doped samples. T_1 = BFX34, T_2 = BFX41, P_1 and P_3 = 50 kΩ, P_2 and P_5 = 5 kΩ, P_4 = 2 kΩ.



ground, or a single unit (+ 30 V) referred to a floating ground.

The timers used here are functionally similar to the more popular LM 555, but with some features that allow a simplified circuit design. The available voltage swing is up to 40 V, the output stage offers the choice of open-collector and open-emitter, and positive and negative logic are available as well as a bootstrap configuration that reduces the switching time.

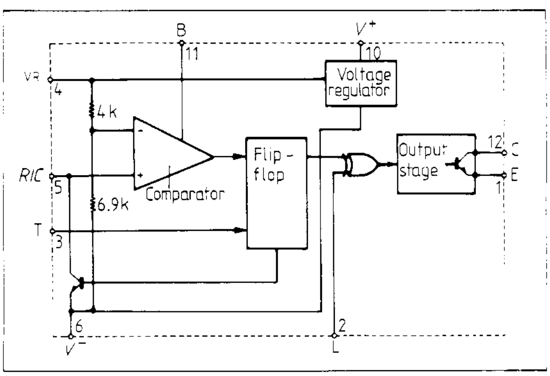
In figure 3 the LM 322 functional block diagram is shown, and in figures 4(*a*) and (*b*) the collector–output and the emitter–output configurations are depicted, with the respective in/out relationships for positive and negative logic.

The large fraction (V_s') of the sweep signal picked up at the collector point probe should be subtracted by a differential amplifier, thus allowing further amplification of the small signal produced by the collected excess carriers (figure 1). The very simple differential amplifier we adopted is made with a single IC (Texas TL082), and it is shown in figure 5. The voltage divider P feeds the fraction αV_s of the sweeping voltage to the buffer OA2 (gain$=1+R_1/R_2$), and the subtraction of V_s' from the collector signal V_c is operated by OA1 (gain at the inverting input $=-R_2/R_1$, and gain at the non-inverting input$=1+R_2/R_1$). The output signal is therefore $V_0=(1+R_2/R_1)(V_c-\alpha V_s)$.

Monitoring V_0 on the oscilloscope screen, the balance condition ($\alpha V_s=V_s'$) can be easily achieved. The signal amplitude can be subsequently increased to the desired value by selecting the gain on the oscilloscope input amplifier. The differential amplifier is powered by two 9 V dry cells and the R_2'' trimmer is adjusted to minimise the common mode gain (i.e. $R_2'+R_2''=R_2$).

The semiconductor bar (approximately $30\times3\times3\ \mathrm{mm}^3$) must be cut out of a single-crystal ingot, not too heavily doped in order to keep the minority carrier lifetime τ longer than the time of flight from emitter to collector.

Figure 3 Functional block diagram of LM 322 IC timer. B, boost; C, collector; E, emitter; L, logic; T, trigger; VR, voltage reference.



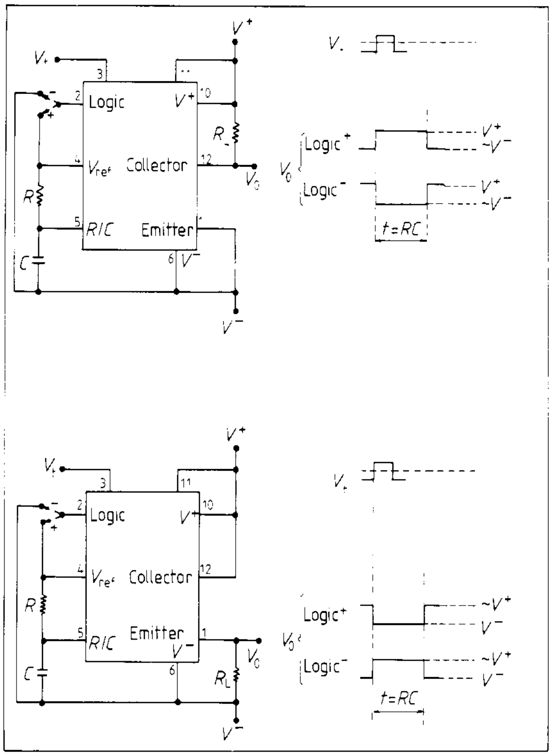
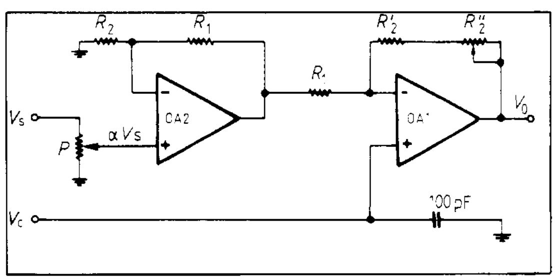


Figure 4 The two monostable configurations of LM 322: (*a*) collector output; (*b*) emitter output.

Silicon single crystals are commonly available at low cost, but low resistance ohmic contacts are more easily obtained using (more expensive) germanium samples. On germanium we made satisfactory ohmic contacts by simply soft-soldering with the standard Pb/Sn alloy. On silicon, on the other hand, a more complicated technique is required: for example a gold (on Si-n) or aluminium (on Si-p) preplating followed by baking in an inert gas atmosphere and finally by a conductive silver–epoxy bonding.

The rectifying point contacts are easily made using thin wires (~0.3 mm diameter) of tungsten or

Figure 5 The differential amplifier circuit. $R_1=1\ \mathrm{k}\Omega$, $R_2=10\ \mathrm{k}\Omega$, $R_2'=8.2\ \mathrm{k}\Omega$, $R_2''=5\ \mathrm{k}\Omega$; $P=10\ \mathrm{k}\Omega$; OA1 = OA2 = ½TL082



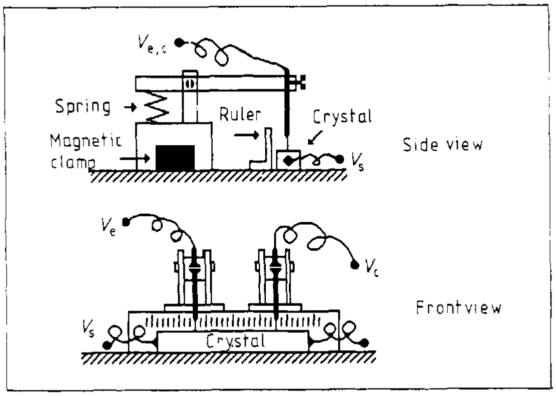


Figure 6 The point probe holder.

phosphor–bronze, which are spring loaded onto the sample by means of an appropriate wire holder (see figure 6). Some care must be taken while handling the sample because the effective carrier lifetime is strongly affected by surface recombination. Very high recombination velocity due to a rough or dirty crystal surface may actually attenuate the signal down to undetectable levels.

A safe procedure is the following: (1) lap the sample with #800 wet carborundum paper, (2) rinse in distilled water, (3) dip the sample in a CP4 etching bath (10% HF, 30% CH_3COOH, 60% HNO_3) for one minute and immediately wash it in distilled water, (4) make the contacts.

4. Measurements of mobility and diffusion coefficient

The shape $n(X, t)$ of the excess carrier pulse can be described analytically, for $E_s = 0$, by solving the transport and continuity equations (see for example McKelvey 1966). Assuming that N_0 excess carriers are injected at $X=0$ in a very short time at $t=0$, one obtains the gaussian spreading:

$$n(X, t) = \frac{N_0 \exp(-t/\tau) \exp(-X^2/4Dt)}{(4\pi Dt)^{1/2}}, \qquad (1)$$

where τ is the lifetime and D the diffusion coefficient of the excess carriers. The pulse width at half height $\Delta X(t)$ as a function of time can be obtained from equation (1), solving the equation $n(\Delta X/2, t) = \frac{1}{2} n(0, t)$:

$$\Delta X(t) = [16\, Dt \ln(2)]^{1/2} = (11.08\, Dt)^{1/2}. \qquad (2)$$

With an applied electric field $E_s \neq 0$, the pulse will be swept past the collector, and if we assume as a first approximation that its shape is still well described by relation (2), the pulse displayed on the oscilloscope is expected to have a width

$$\Delta t_0 = \Delta X / v, \qquad (3)$$

or, with the assumption $\Delta t_0 \ll \tau$:

$$\Delta t_0 = (11.08\, Dt_0)^{1/2}/(d/t_0) = (11.08\, D)^{1/2} t_0^{3/2}/d. \qquad (4)$$

A plot of the measured Δt_0 against $(t_0^{3/2}/d)$ should therefore be a straight line.

Moreover from the relations (2) and (3) we get $11.08\, Dt_0 = (\Delta X)^2 = (v \Delta t_0)^2 = vv(\Delta t_0)^2 = (d/t_0)(\mu E_s)(\Delta t_0)^2$ so that we can express the ratio D/μ in terms of measurable quantities as

$$D/\mu = (\Delta t_0 / t_0)^2 d E_s / 11.08. \qquad (5)$$

The measured D/μ should be compared with the value predicted by the Einstein relation

$$D/\mu = k_B T/e, \qquad (6)$$

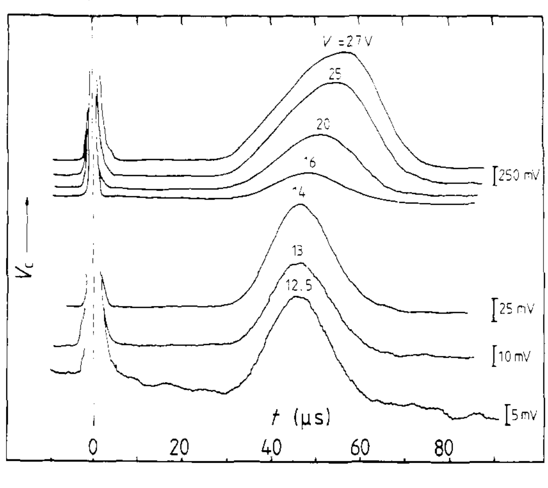
which at room temperature gives $D/\mu = 0.026$ V.

A typical set of observed signals, obtained with an n-doped Ge sample (of resistivity $\sim 15\ \Omega$ cm) and using different injecting pulse amplitude V_i, is shown in figure 7.

A systematic dependence both of the collector pulse width at half height (Δt_0) and of the time of flight t_0 on the injecting pulse amplitude V_i is apparent. Such an effect is due to the perturbation of the electric field inside the crystal produced by the injected excess carriers, and therefore a correct measurement should be performed with a vanishingly small injection.

This condition however would produce a weak signal buried in noise, which can only be recovered by using an expensive storage oscilloscope with the 'average' facility. An alternative solution (not requiring the storage oscilloscope) is to extrapolate the values obtained with a substantial injection to zero injection, i.e. to $V_i = V_e$, where $V_e = V_s X_e / l$ is the voltage of the sample point where the emitter probe is placed (X_e is the distance from the sample end connected to ground).

Figure 7 The collector signals recorded with various injecting voltages V_i. The sweep voltage V_s is 20 V and the drift distance is 0.5 cm.



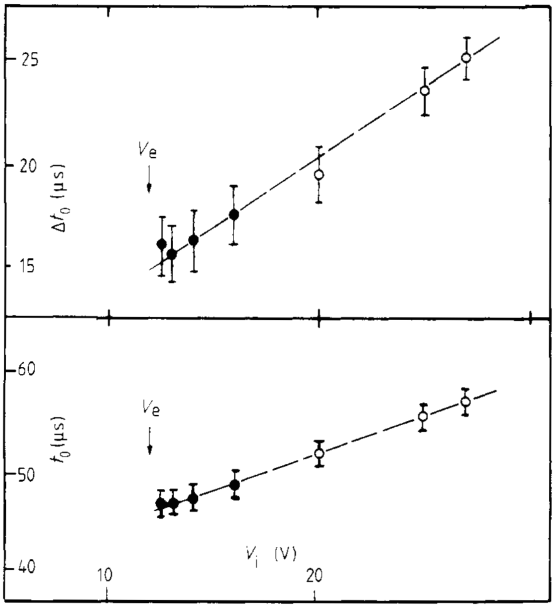


Figure 8 Effect of the injecting pulse amplitude V_i on t_0 and Δt_0. The data are obtained from the records of figure 6.

In figure 8 the Δt_0 and t_0 values obtained from the records of figure 6 are plotted against the injecting pulse amplitude V_i. Full circles indicate the measurements taken with the storage oscilloscope (low injection), averaged over many signal acquisitions, while the open circles are single acquisitions (high injection). The effect of the field perturbation disappears at the lowest V_i values giving constant Δt_0 and t_0 values. The linear extrapolation, however, from data taken with large V_i to $V_i = V_e$, gives practically the same result.

We present in table 1 some experimental data obtained with the same Ge-n crystal and various sweep voltages V_s. The drift distances d were measured by reading the point probe separation on a millimetre scale placed behind the sample. From these data we obtain for D/μ the mean value 0.027 ± 0.001, in good agreement with the one predicted by the Einstein relation. The slightly higher experimental result is due

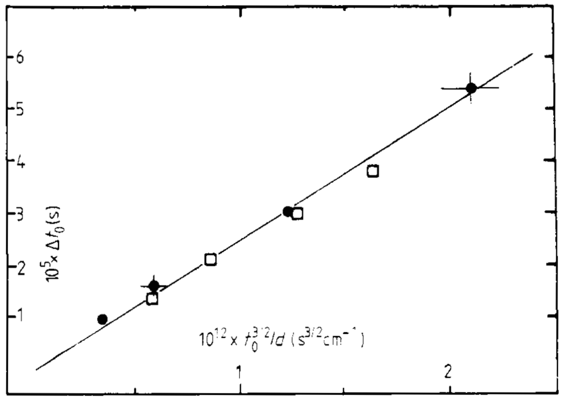


Figure 9 Check of the expected linear dependence of Δt_0 on $t_0^{3/2}/d$. □, $d = 0.81$ cm; ●, $d = 0.50$ cm.

to the finite duration of the injected pulse. The linear dependence of Δt_0 on $(t_0^{3/2}/d)$, predicted by equation (4) is well followed by the experimental data, as shown in figure 9.

The hole mobility values obtained with different sweep fields are also reported in table 1. Here the observed field dependence of the mobility is due to the excess-carrier diffusion and recombination processes. A detailed analysis of this effect was performed by McKelvey (1956), who suggested the correction formula

$$\mu_c = \mu_0[(1 + X^2)^{1/2} - X]$$
$$X = 2k_B T(t/\tau + 0.5)/(eE_s d). \qquad (7)$$

Here μ_0 and μ_c are the observed and corrected mobilities respectively, k_B is the Boltzmann constant, T the absolute temperature, e the electron charge and τ the excess carrier lifetime.

Equation (7) predicts large corrections for small sweep fields. It is simple to explain such behaviour qualitatively in the limit of zero field. In fact, with the excess carriers injected at $X = 0$ at time $t = 0$, one should expect to observe at some fixed position X' firstly an increasing carrier concentration (due to the diffusive spread), followed by a decrease down to the original equilibrium value (due to recombination). If

Table 1 Experimental data

d (cm)	V_s (V)	t_0 (μs)	μ_0 ($cm^2 V^{-1} s^{-1}$)	Δt_0 (μs)	D/μ (V)	$10^{12} \times t_0^{3/2}/d$ ($s^{3/2} cm^{-1}$)
0.81 ± 0.02	12 ± 0.1	121 ± 3	1950 ± 68	38 ± 2	0.0247	1.64
0.81 ± 0.02	15 ± 0.1	102 ± 3	1850 ± 71	30 ± 2	0.0271	1.27
0.81 ± 0.02	20 ± 0.1	78 ± 2	1820 ± 65	21 ± 2	0.0303	0.85
0.81 ± 0.02	25 ± 0.1	64 ± 2	1770 ± 70	13.5 ± 1.5	0.0232	0.63
0.50 ± 0.02	8 ± 0.1	108 ± 3	2025 ± 99	54 ± 3	0.0258	2.24
0.50 ± 0.02	12.6 ± 0.1	72 ± 2	1930 ± 94	30 ± 2	0.0282	1.22
0.50 ± 0.02	20 ± 0.1	47 ± 2	1860 ± 109	16 ± 2	0.0298	0.64
0.50 ± 0.02	28.2 ± 0.1	33.5 ± 1.5	1850 ± 110	9.5 ± 1.5	0.0292	0.39

t' is the time of maximum concentration at X', the zero-field drift velocity $v' = X'/t'$ should be finite corresponding to an infinite observed mobility. By extension, with any sweep field value one expects the observed mobility to be larger than the true one.

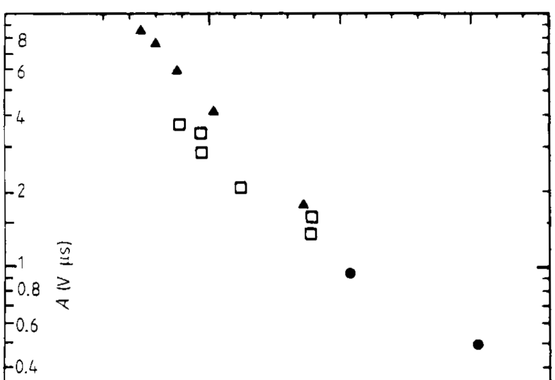
However, the correction formula (7) requires knowledge of the carrier lifetime value τ. This can be directly measured using, for instance, the simple technique we have described elsewhere (Sconza and Torzo 1985), but a rough estimation can also be obtained from the exponential decay of the collector signal area. This area $A = \int V_c(t')\,dt'$ is in fact proportional to the excess-carrier density $n(t)$ drifting beneath the collector, which decreases exponentially with time according to equation (1), so that:

$$A(t) = A_0 \exp(-t/\tau). \qquad (8)$$

By using equation (8) one can evaluate τ from measurements of $A(t_0)$ taken with different t_0 values at constant injection. In figure 10 the pulse areas, measured at three constant drift distances d with different sweep field values E_s, are plotted against the corresponding times of flight t_0. In order to have a constant injection the injecting pulse amplitude V_i was varied with E_s, following the relation $V_i = V_s X_e/l + \Delta V$, where ΔV is a constant bias voltage applied to the diode D_e (we used $\Delta V = 3$ V).

From figure 10 we obtained $\tau \simeq 50\,\mu$s and using this value we corrected the mobility measurements according to equation (7). The corrected values μ_c (figure 11) show no more V_s dependence. Their

Figure 10 The collector pulse area A plotted against the time of flight t_0. The data are obtained with an emitter bias voltage $\Delta V = 3.0$ V. ▲, $d = 0.31$ cm; □, $d = 0.48$ cm; ● = 0.80 cm.



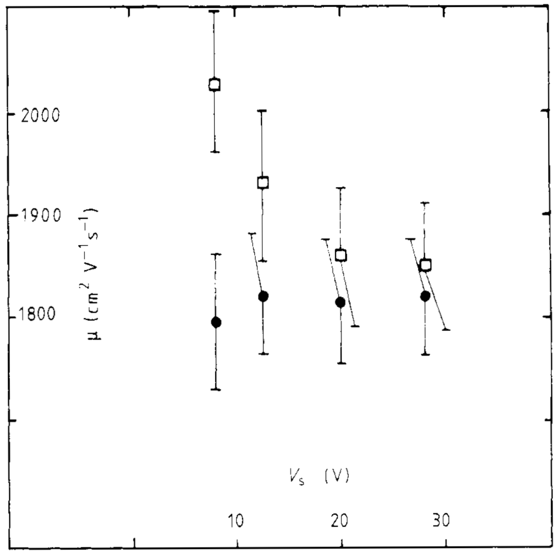


Figure 11 The observed (μ_0, □) and the corrected (μ_c, ●) hole mobilities plotted against the sweep field for a drift distance $d = 0.5$ cm.

average is slightly lower than the accepted value ($\mu = 1900$ cm^2 V^{-1} s^{-1}) for holes in high-resistivity Ge-n samples (Prince 1953), because in our straightforward approach the end contact resistances have been neglected, by assuming $E_s = V_s/l$. This systematic error can easily be avoided by performing a set of measurements of the voltage V_c for several positions X of the collector point probe, and by evaluating the actual sweep field as $E_s = \Delta V_c/\Delta X$.

5. Conclusions

The Haynes–Shockley experiment in the version described here is well suited for an undergraduate laboratory course devoted to solid-state and semiconductor physics. The experiment can be performed at two different levels.

(1) Freshman level: a direct demonstration of the transport properties of holes (electrons) in semiconductors can be easily accomplished by making a single measurement of time of flight in Ge-n (Ge-p) with 'high' sweep and 'weak' injection. At this level the teacher should suggest the appropriate value for V_i and the student's effort should be devoted essentially to measure t_0 as a function of V_s for different point probe positions. By observing that the pulse spread and attenuation increase with the probe separation, he or she will have a qualitative proof of the diffusion and recombination processes.

(2) Advanced level: several sets of Δt_0 and t_0 measurements taken with different V_i, V_s and d values should offer to the student a deeper understanding of the non-equilibrium processes in semiconductors, and

some confidence in handling the experimental parameters which affect the measurement. The experiment could easily be extended to study the mobility dependence on the temperature and on the doping level (Prince 1953), by thermoregulating the sample holder at different temperatures and by using Ge samples of different resistivities. At this level also the construction of the simple pulser and amplifier circuitry could be assigned to the student as an exercise.

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