An improved version of the Haynes–Shockley experiment with electrical or optical injection of the excess carriers

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The Haynes–Shockley experiment allows direct measurements of the drift mobility, of the diffusion coefficient, and of the recombination lifetime of excess carriers in semiconductors. In order to obtain easier and more accurate measurements in a didactic laboratory, we designed a new setup for this experiment that uses electrical or optical injection of the excess carriers.

I. INTRODUCTION

The time-of flight method, first introduced by Haynes and Shockley[1] to measure the electron and hole mobility, is now a standard technique for investigating semiconductor properties. 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 behavior.

While the experiment is conceptually very simple, it is usually not easy to execute due to some experimental difficulties that may spoil its didactic efficacy: the main problems are related to the point probes used to inject and to detect the excess charges.

In this paper we describe a new experimental setup that offers several advantages over the one we proposed some years ago.[2] The most important is the possibility of injecting the excess carriers not only by an electric pulse, as usual, but also by means of a short light pulse produced by an infrared laser diode.

In Sec. II we review the essential features of the Haynes–Shockley experiment, in Sec. III we describe our new experimental setup, in Sec. IV we give some experimental results for mobility and diffusion coefficients in Ge and Si, and in Sec. V, we give an example of how to obtain the recombination lifetime from the area of the collected pulses.

II. THE ORIGINAL HAYNES–SHOCKLEY EXPERIMENT

In the Haynes–Shockley experiment, a *p*-doped[3] semiconductor bar has two Ohmic contacts soldered at the ends. One of these bias contacts is grounded, and a negative voltage V_s is applied to the other,[4] producing an electric field E_S (sweep field) across the sample. Two metallic point probes E and C, separated by a distance *d*, are placed in contact with the sample as shown in Fig. 1. These point-contacts are depicted as diodes D_E and D_C because they behave as partially-rectifying contacts.

When a short ($\leqslant 1\ \mu$s) negative voltage pulse V_I is applied to the electrode *E*, with an amplitude sufficient to forward bias the diode D_E, a burst of excess electrons is injected into the sample. Immediately, i.e., within a time of the order of the dielectric relaxation time ϵ/σ, where ϵ is the dielectric constant and σ the electrical conductivity of the sample ($\epsilon/\sigma \approx 10^{-12}$ s), this excess of negative charge is compensated by an equal excess of positive charge.

The sweep field makes the electrons and holes drift together[5] *toward* the grounded electrode with a mean velocity $v_d = \mu_{\text{amb}} E_S$, where $\mu_{\text{amb}} = \mu_n \mu_p (p-n)/(\mu_n n + \mu_p p)$ is the ambipolar mobility, which approximates the minority carriers mobility in sufficiently doped semiconductors.

After a delay t_0 those excess carriers that have survived recombination will reach the sample region underneath the point probe C. The diode D_C, which is reverse biased by the resistor R_b, acts as a collector for *minority* carriers (electrons in the present case). Therefore, a weak current of electrons flows through R_b, and only when the burst of excess carriers reaches the collector region does this current increase, due to the larger density of free electrons, and a negative pulse across R_b can be detected by an oscilloscope. Actually two peaks appear at the collector for each injected pulse (see the insert in Fig. 1). The first peak (with amplitude and width similar to those of the pulse applied to the emitter) is due to the injection pulse propagating from E to C at the speed of light in the semiconductor material; therefore it is practically simultaneous with the injection pulse. The second peak is due to the excess carriers flowing past the collector and it is much smaller and broader, owing to diffusion and recombination processes.

Moreover, both peaks are superimposed on the fraction αV_s $(0<\alpha<1)$ of the sweep voltage V_s, which is seen by the collector point. It is necessary to subtract from the collector signal the underlying sweep signal to be able to amplify and detect the small signal due to the excess carriers. This can be achieved by passing the collector signal through a differential amplifier, as described in Sec. III E.

The separation of the two peaks on the oscilloscope time scale yields the carrier time of flight t_0. The drift velocity is then obtained as $v_d = d/t_0$ and the mobility as

$$\mu = v_d/E_s = dL/(V_s t_0), \tag{1}$$

where V_s is the sweep voltage, L the sample length, and $E_s = V_s/L$ is the sweep field, within the approximation of negligible resistance for the end contacts.

Information on the diffusion and recombination of the excess carriers can be obtained by measuring the width at half-maximum Δt and the area A of the collected pulse. The ratio of diffusion coefficient D to mobility can be evaluated through the relation (see Ref. 2)

$$\frac{D}{\mu} = \frac{dE_s}{16 \ln 2}\left(\frac{\Delta t}{t_0}\right)^2, \tag{2}$$

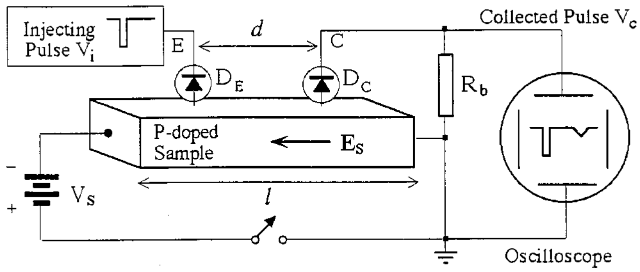

Fig. 1. Block diagram of the Haynes Shockley experiment: D_E and D_C are the emitter and collector point probes.

and the result may be compared with that predicted by the Einstein relation, $D/\mu = kT/e$, where k is the Boltzmann constant, e the elementary charge, and T the absolute temperature.

Finally, the recombination lifetime τ_R is related to the area A of the collector pulse and to the time of flight t_0 by the relation (see Ref. 2)

$$A(t_0) = \text{const} \exp(-t_0/\tau_R). \tag{3}$$

The setup described above is more or less the original one used by Haynes and Shockley and in all later versions of their experiment,[6] the main differences being in the choice of the particular devices used to produce the pulsed bias (required to avoid excessive Joule heating of the sample), to generate the injecting pulse applied to the emitter, or to detect and record the pulse at the collector.

The didactic apparatus we previously used[2] was quite simple, but it offered limited values of the sweep field and of the amplitude of injection pulse, and therefore it was hardly usable with samples of low resistivity and/or short lifetime.

On the other hand, the injection efficiency through the point-contact electrode may be spoiled by wearing and oxidation of the point probe,[7] making the emitter behavior quite unpredictable. This difficulty may be completely avoided by producing the excess carrier through the internal photoelectric effect.

The electronics were therefore redesigned to avoid both these difficulties: our new setup includes the optical-injection mode, described in Sec. III, and the comparison between the two operating modes is made in Sec. IV.

III. EXPERIMENTAL APPARATUS

A. Optical injection

Photons with wavelength below the threshold value $\lambda = hc/E_g$ can interact with the electrons in the valence band of the semiconductor sample and generate electron–hole pairs in excess with respect to the equilibrium density. Therefore, we can obtain a suitable excess carrier burst, if we are able to produce a light pulse of sufficiently high intensity and small duration, and to focus it within a sufficiently small area of the sample.

Sufficient light intensity and focusing are offered by infrared laser diodes[8] coupled to 100–200 μm diam optical fibers. The light power emitted by the laser is quite high (of the order of 10 W with a peak current of about 10 A) so that a sufficient light intensity can be obtained at one end of the optical fiber simply by placing the other end (enclosed in the standard ferrule) on top of the diode case, thus avoiding the painstaking alignment required to achieve optimum optical coupling. Even a reduction of 90% of the available power (peaking at more than 10^4 W/cm^2) leaves enough light output at the free end of the fiber. This end of the optical fiber is then positioned on top of the sample by means of the same simple device used in our old apparatus[2] to hold the needles that act as point contacts.

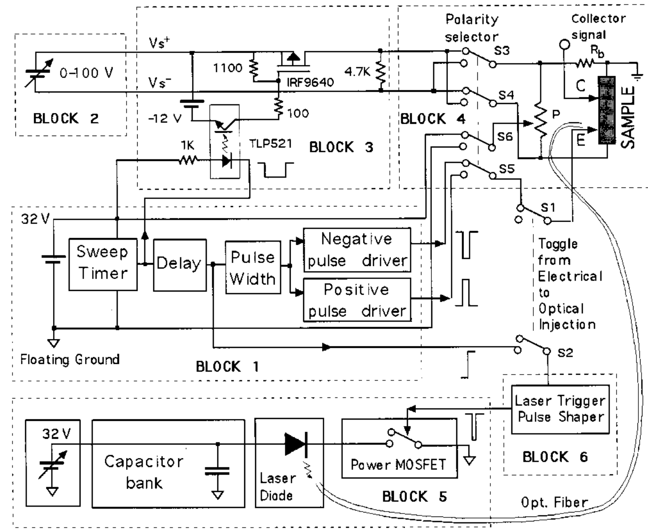

Fig. 2. Block diagram of the double pulser.

B. The double pulser

We built a double pulser for both electrical and optical injection. The improvements with respect to previous design are the following.

(i) The sweep voltage may be pushed up to 50 V (or even to 100 V, in the high range mode), a noticeable advantage when the sample is very long and/or it has a very short recombination lifetime.

(ii) The electrical injection pulse can be made very short ($\geq$100 ns), and its amplitude very high (up to 30 V above the sample potential in the emitter contact position), a feature that becomes important for short recombination lifetimes.

(iii) Problems of instability of the emitter contact may be avoided by using optical injection, with the further advantage of a very short ($10 \leq t_L \leq 200$ ns) duration and a large intensity, which is nearly proportional to the voltage bias of the laser diode.

The block diagram of the double pulser is shown in Fig. 2.

Block 1 is similar to the double pulser described in our previous paper. It provides the timing for the sweeping and, after an adjustable delay, both the injecting pulse and the LASER TRIGGER (electric or optical injection is selected by toggling the switches S1/S2). It is powered by a floating power supply of 32 V, and includes two current amplifiers: one for positive and one for negative injection pulses (adjustable from 0 to 30 V) for the emitter point contact. The pulse polarity is selected (together with the sweep polarity) by the switches S5/S6. The detailed circuitry of block 1 is shown in Fig. 3.

The sweep pulse is produced by connecting the semiconductor sample ends through switches S3/S4 (which select positive or negative polarity) to a second floating power supply (block 2), ranging from 0 to 50, or from 50 to 100 V, during the time of ‘‘sweep on,’’ by means of a power

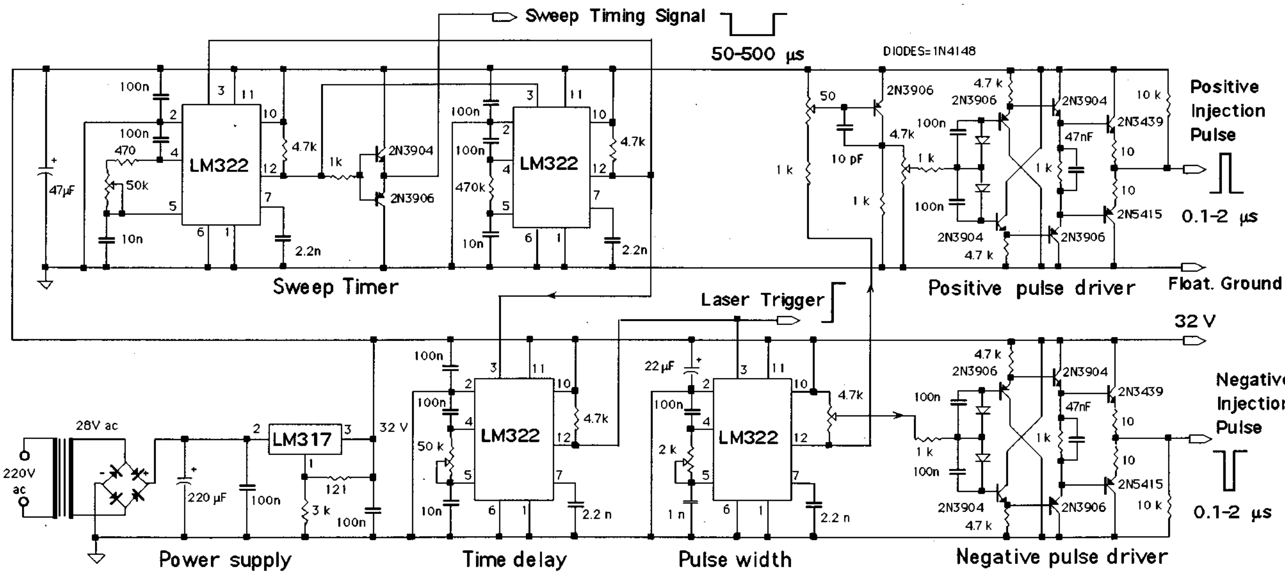

Fig. 3. Block 1. Sweep timer and pulse generator.

MOSFET driven by an optocoupler (block 3, Fig. 2). The sweep duration is adjustable from ≈50 μs to ≈500 μs. The detailed circuitry of block 2 is shown in Fig. 4.

C. Pulses for electrical injection

In order to make effective the point probe injection, the injection pulse signal V_I must drive the point probe E at a voltage much lower (in the case of a P doped, or higher for an N doped sample) than the sample voltage at the E contact point. To produce a submicrosecond pulse with amplitude as high as 50 V (or 100 V) is not easy, because it does require a very high slew rate; therefore we chose to limit the pulse maximum amplitude within ±30 V while adding it to the fraction of the sweep signal V_S selected by the potentiometer P (1 kΩ) connected in parallel to the sample. The P wiper potential should be set equal to the sample potential V_{E} at the

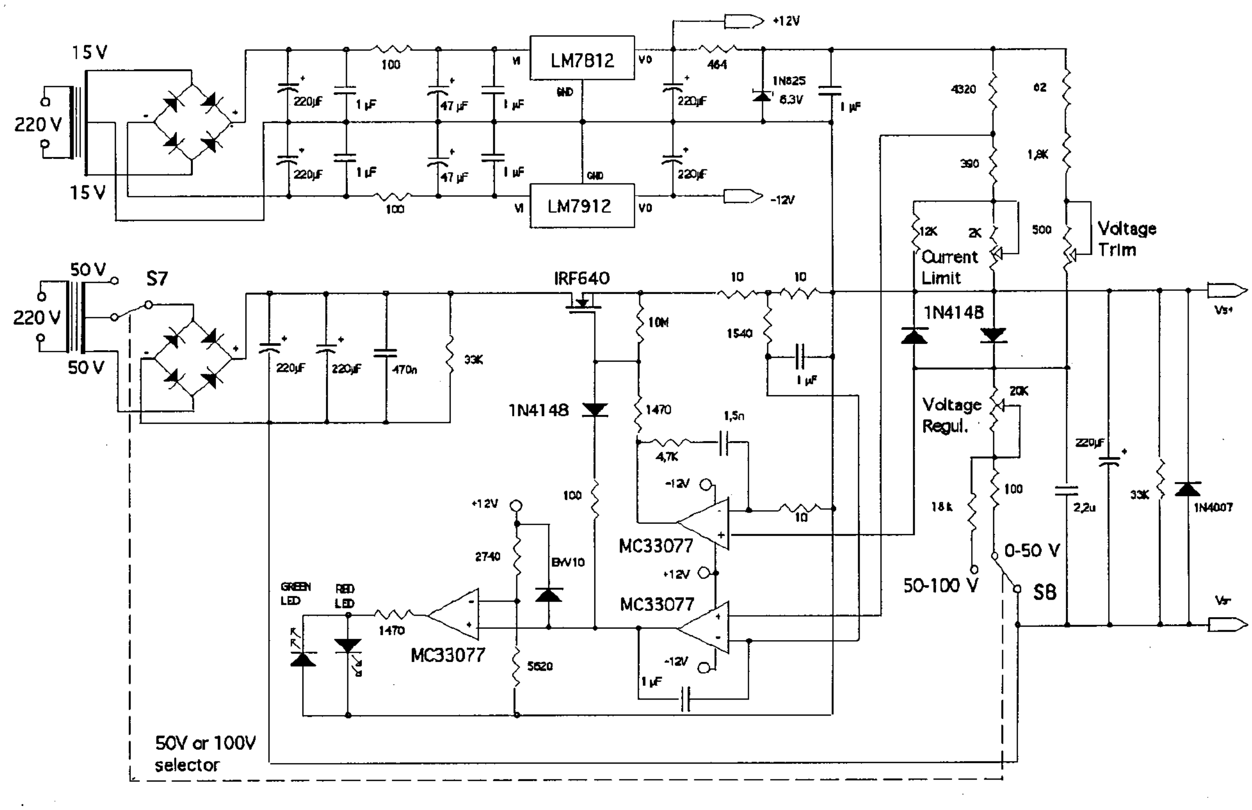

Fig. 4. Block 2. Floating power supply.

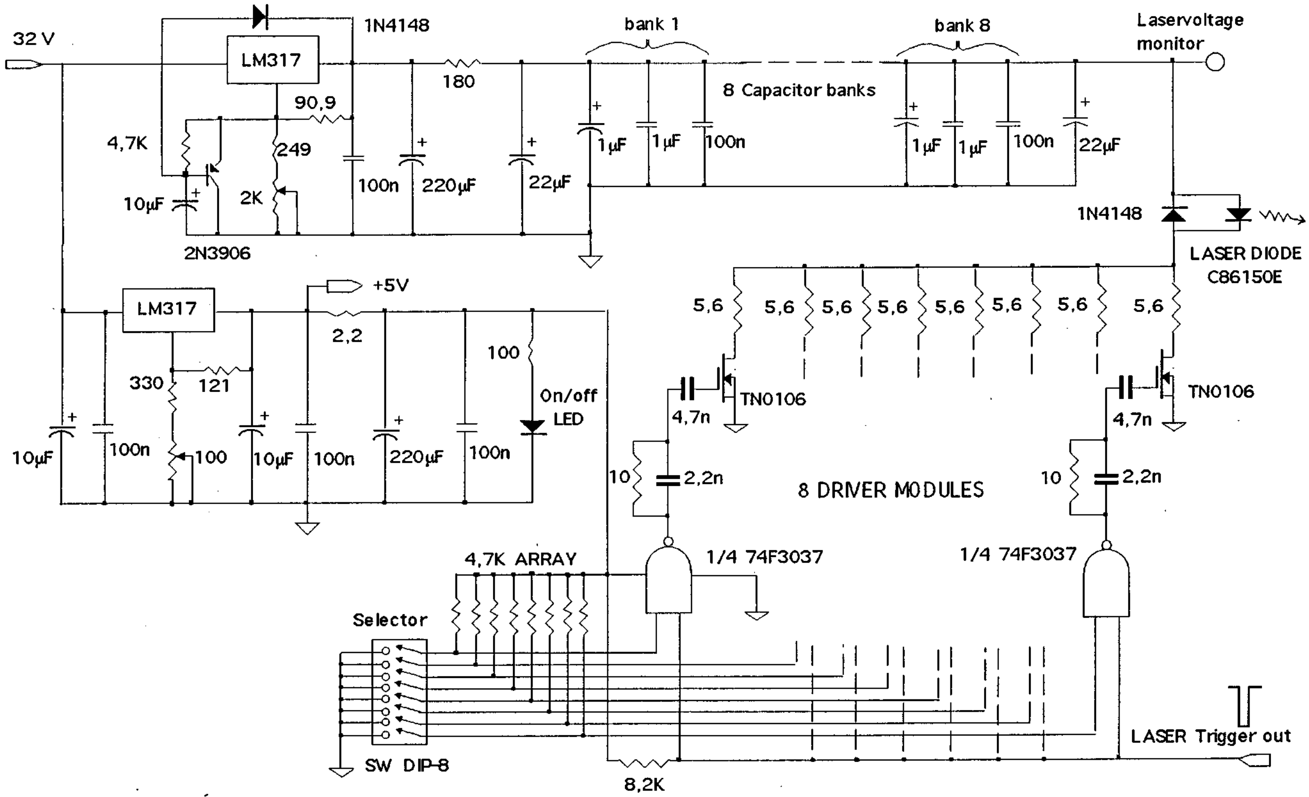

Fig. 5. Block 5. Laser driver.

contact point E [e.g., $V_p = (\frac{1}{2})V_S$ when the emitter is placed on the midplane of the sample]. This feature also makes the measurements simpler because, with constant V_I amplitude, the emitter efficiency becomes roughly independent on the sweep field value.

D. Pulse for optical injection

The laser pulse is produced by fast discharging a bank of capacitors through the laser diode by means of several (up to eight) power MOSFETs connected in parallel (block 5, Fig. 5). Each MOSFET may be separately enabled or inhibited by NAND gates and a multiple selector in order to trim the maximum current. For the C86150 laser diode the maximum current (about 16 A) is obtained using eight MOSFETs in parallel, but a sufficient performance is achieved even with only two MOSFETs.

The trigger signal for the discharge is obtained from the timing block 1 through a shaping circuit (block 6, Fig. 6). In this block the laser trigger input (‘‘Laser Trigger in’’) is split into two signals: the first one is delayed by a constant amount by two 7414 inverters, the second one is delayed by

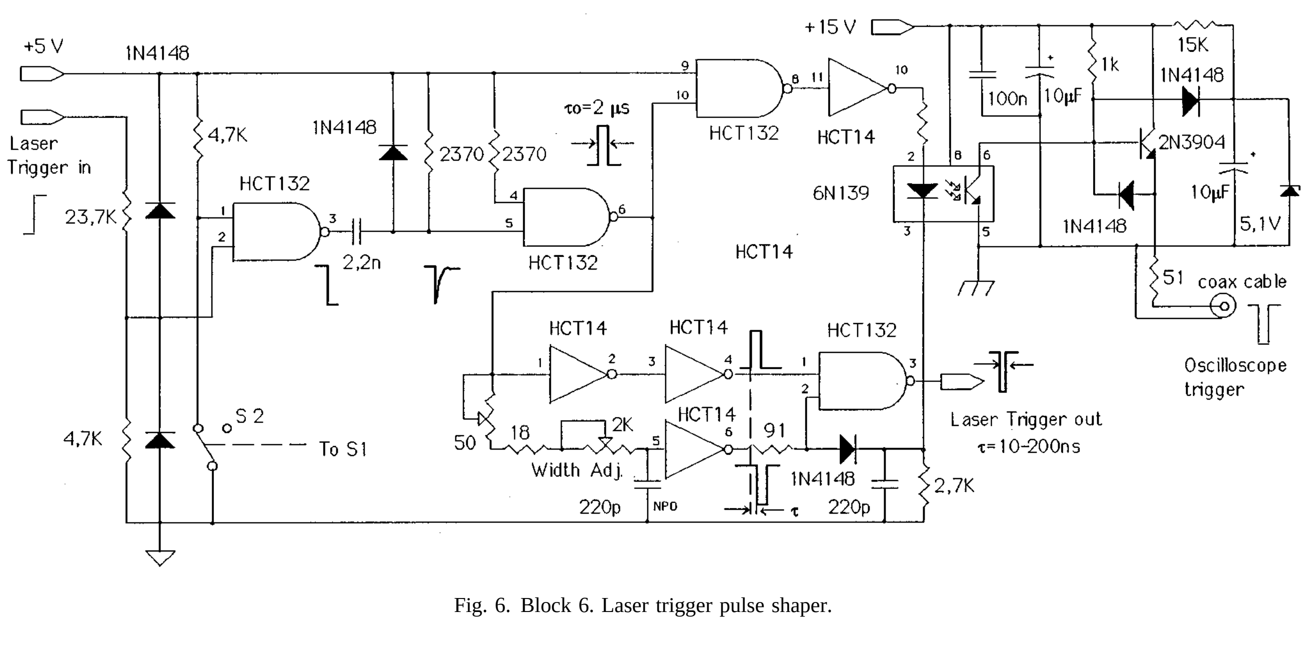

Fig. 6. Block 6. Laser trigger pulse shaper.

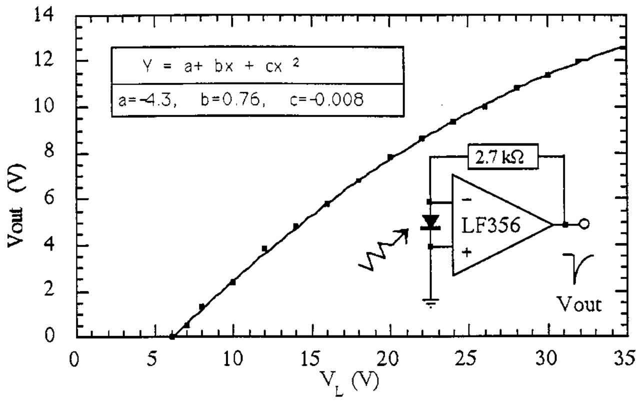

Fig. 7. Light output of the optical fiber versus laser bias voltage.

an adjustable amount by a RC filter and a single inverter. Both are fed to a 74132 NAND gate that produces an output pulse (''Laser trigger out'') suitable to trigger the laser diode, and whose duration can be adjusted from 10 to 200 ns.

Another circuit (in block 6) produces an optoisolated TTL pulse whose front edge is synchronous with the laser current pulse, to be used as an oscilloscope trigger.

The laser output power may be adjusted by changing (in the range 4–32 V) the voltage V_L across the condenser bank.

We monitored the light intensity at the fiber output using a fast photodiode (Motorola MRD 500 with zero bias voltage) and a current to voltage converter (see the insert in Fig. 7). The amplitude of the V_{out} signal (which is proportional to the light output intensity I), read on the oscilloscope screen, is presented in Fig. 7 as a function of the voltage V_L. The shape of the $I(V_L)$ curve is well fitted by a second-order polynomial and it is practically zero for $V_L = 6$ V (threshold voltage).

E. The collector signal detection

In order to subtract the fraction of the sweep signal V_S seen by the collector from the collector signal V_C, we pass it through the differential amplifier shown in Fig. 8, where we use a differential gain of $\frac{1}{3}$, to allow V_C signal amplitudes as high as ± 45 V[9] without driving the operational amplifier inputs beyond the ± 15 V range of the power supply.

The output signal V_0 of the differential amplifier is finally displayed on the screen of a digital oscilloscope (e.g., Tektronix TDS 220) and recorded on a PC through an interface card.

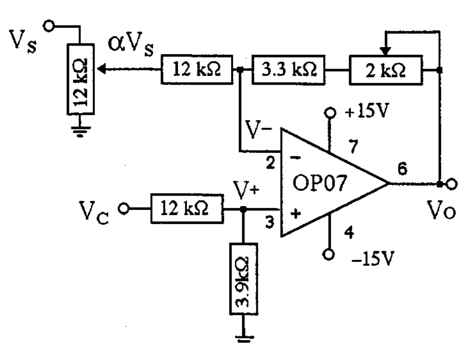

Fig. 8. The differential amplifier.

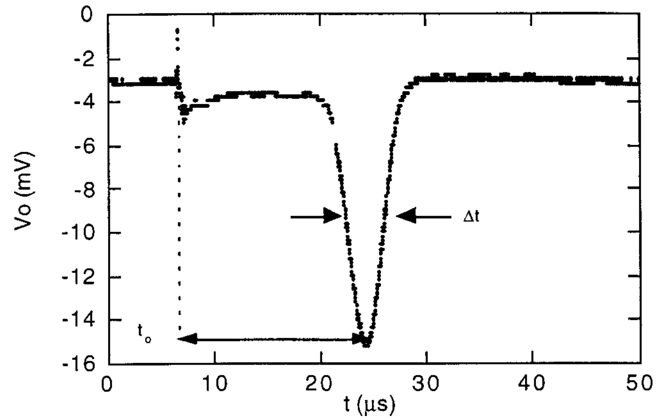

Fig. 9. Waveform observed in a P-doped Ge sample ($\rho = 15\ \Omega$ cm) with optical injection.

IV. MEASUREMENTS OF THE MOBILITY AND OF THE DIFFUSION COEFFICIENT

A. Measurements with P-doped Ge samples

Figure 9 presents one waveform obtained, using optical injection, with a P-doped Ge sample whose dimensions are $3.60 \times 0.3 \times 0.3\ \text{cm}^3$, and resistivity about 15 Ω cm. The measurement was taken with a sweep potential $V_S = 40$ V, and a distance between the collecting point and the optical fiber end $d = (7.1 \pm 0.1)$ mm (measured with a small telescope mounted on a micrometric screw). The laser voltage was $V_L = 8.8$ V and the sample temperature 28.6 °C.

The excess carrier injection slightly modifies the sweep field in the sample, and this affects the drift time t_0 and the half-maximum width Δt. To account for this effect, one must extrapolate the measured t_0 and Δt values to zero excess carriers injection. Figure 10 reports some measurements of t_0 and Δt taken while gradually reducing the laser diode bias voltage V_L from 30 to 7 V (i.e., close to zero light injection).

The extrapolated values $t_0 = (17.2 \pm 0.1)\ \mu$s and $\Delta t = (3.4 \pm 0.1)\ \mu$s yield, for the drift mobility, $\mu = (3715 \pm 74)\ \text{cm}^2\,\text{V}^{-1}\,\text{s}^{-1}$ and for the ratio of diffusion coefficient to mobility the value $D/\mu = (0.027 \pm 0.002)$ V. The error intro-

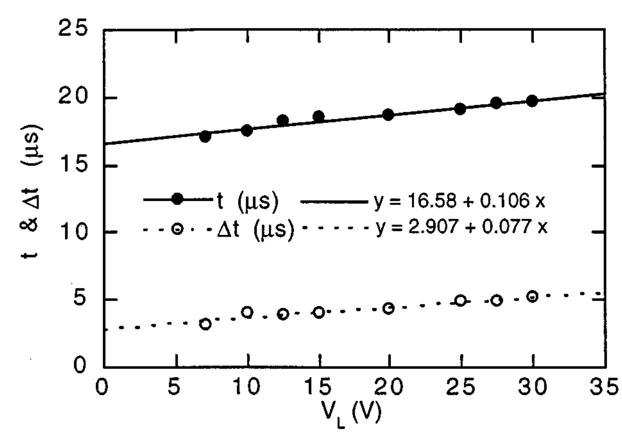

Fig. 10. Drift time t_0 and pulse width at half-maximum Δt versus laser diode voltage V_L.

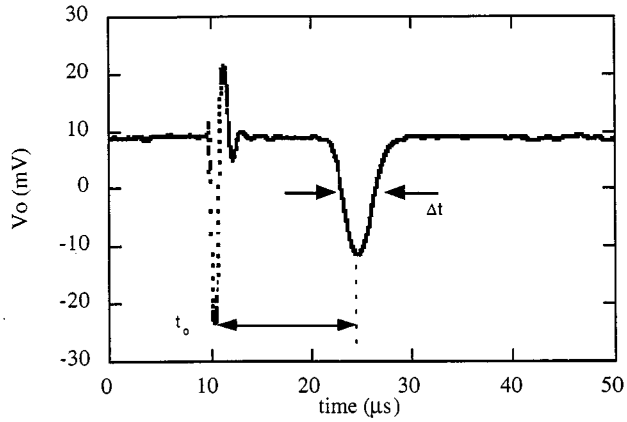

Fig. 11. Waveform observed in a P-doped Ge sample ($\rho=15\,\Omega$ cm) with electrical injection.

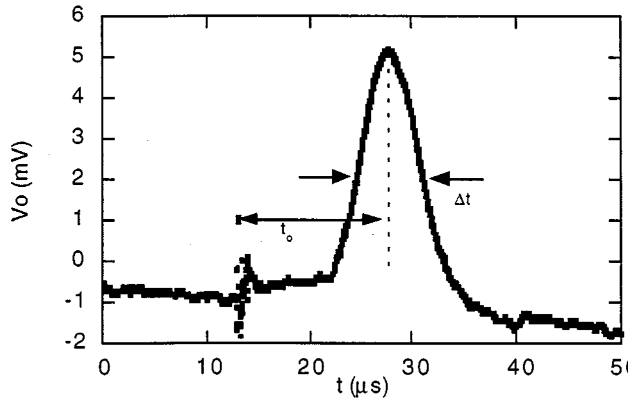

Fig. 12. Waveform observed in an N-doped Ge sample ($\rho=1\,\Omega$ cm) with optical injection.

duced by the sweep field modification due to the injected carriers becomes negligible with moderate light injection (say $V_L \leqslant 10$ V).

One should introduce a further small correction because a fraction of the applied potential (sweep signal) drops across the contact resistances. For the present sample, the contact resistances are only 2% of the sample resistance, so that the effective V_S value is 39.2 V and the calculated mobility becomes $\mu=(3791\pm75)\ \mathrm{cm^2\,V^{-1}\,s^{-1}}$ and $D/\mu=(0.0265\pm0.002)$ V, to be compared with the known values (at $T=300$ K): $\mu=3900\ \mathrm{cm^2\,V^{-1}\,s^{-1}}$ and $D/\mu=kT/e=0.026$ V.

Similar results may also be obtained using electrical injection. With the same sample and a moderate level of injection (amplitude$\approx$10 V, width$=$0.3 μs) we obtained the waveform of Fig. 11.

In this measurement the distance between emitter and collector was $d=(6.05\pm0.10)$ mm, the sweep voltage $V_S=40$ V, and the sample temperature 26 °C.

The measured time of flight is $t_0=(14.3\pm0.1)\ \mu$s and the width at half-maximum is $\Delta t=(3.0\pm0.1)\ \mu$s, yielding $\mu=(3808\pm85)\ \mathrm{cm^2\,V^{-1}\,s^{-1}}$ and $D/\mu=(0.0267\pm0.002)$ V. Correcting for the contact resistances $\mu=(3885\pm87)\ \mathrm{cm^2\,V^{-1}\,s^{-1}}$ and $D/\mu=(0.0262\pm0.002)$ V.

B. Measurements on heavily doped Ge N sample ($\rho=1\ \Omega$ cm)

Due to the small resistivity, it was necessary to cut the sample as a long and thin bar ($1.5\times1.5\times40$ mm) to achieve a resistance of some hundred ohms. The sample was carefully polished with diamond and alumina powders and then etched in CP4[10] for several minutes in order to have a sufficiently long recombination lifetime.

The waveform obtained with a sweep voltage $V_S=38$ V, $L=40$ mm, a distance $d=(2.30\pm0.05)$ mm, and $V_L=10$ V, is shown in Fig. 12: here $t_0=(14.9\pm0.1)\ \mu$s and $\Delta t=(5.7\pm0.2)\ \mu$s yielding $\mu=(1625\pm100)\ \mathrm{cm^2\,V^{-1}\,s^{-1}}$ and $D/\mu=(0.029\pm0.002)$ V.

This value should be corrected for the effects of diffusion and recombination (the so-called McKelvey correction[11]) that are not negligible due to the small recombination lifetime of this thin sample. According to McKelvey, the corrected mobility is $\mu_{\mathrm{corr}}=\mu[\mathrm{sqrt}(1+x^2)-x]$, with $x=2kT(t/\tau_R+\frac{1}{2})/(eV_S d/L)$, where k is the Boltzmann constant, T the absolute temperature, and τ_R the recombination lifetime. In our case the x parameter was estimated as $x\approx0.03$, assuming for the recombination lifetime $\tau_R=20\ \mu$s, so that $\mu_{\mathrm{corr}}=(1577\pm96)\ \mathrm{cm^2\,V^{-1}\,s^{-1}}$.

In low resistivity samples, the Joule heating becomes important: during the measurement shown in Fig. 12, the sample temperature was quite high (41.5 °C, as measured by a thermocouple).

For Ge with a resistivity of 1 Ω cm one expects a hole mobility $\mu_0\approx1700\ \mathrm{cm^2\,V^{-1}\,s^{-1}}$ with a temperature dependence: $\mu=\mu_0(T/T_0)^{-2.3}$ (see Ref. 6). Therefore at a temperature of the order of 315 K, the predicted values are $\mu=1520\ \mathrm{cm^2\,V^{-1}\,s^{-1}}$ and $D/\mu=kT/e=0.0272$ V.

The same sample was measured also with electric injection (Fig. 13). The conditions of the measurement were $d=2.72$ mm, $L=40.0$ mm, $V_S=38$ V, injecting pulse: amplitude$\approx$6 V, width$\approx$0.3 μs, temperature$=$40 °C. The measured values $t_0=17.5\ \mu$s and $\Delta t=5.6\ \mu$s yield $\mu=(1636\pm100)\ \mathrm{cm^2\,V^{-1}\,s^{-1}}$ and $D/\mu=(0.025\pm0.002)$ V. Applying the McKelvey correction ($x\approx0.03$, with $\tau=20\ \mu$s), one gets $\mu=(1588\pm97)\ \mathrm{cm^2\,V^{-1}\,s^{-1}}$. The expected value is $\mu=1542\ \mathrm{cm^2\,V^{-1}\,s^{-1}}$.

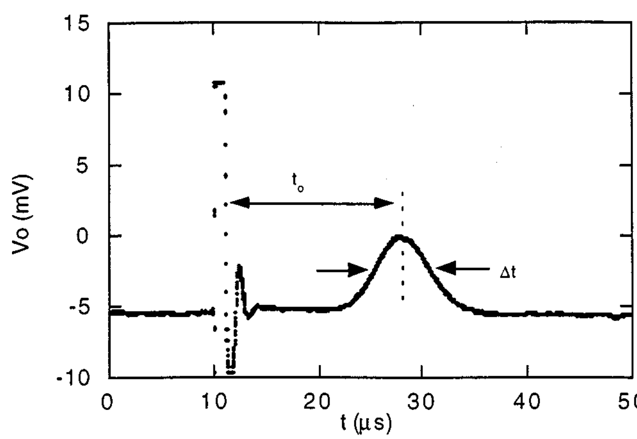

Fig. 13. Waveform observed in an N-doped Ge sample ($\rho=1\ \Omega$ cm) with electrical injection.

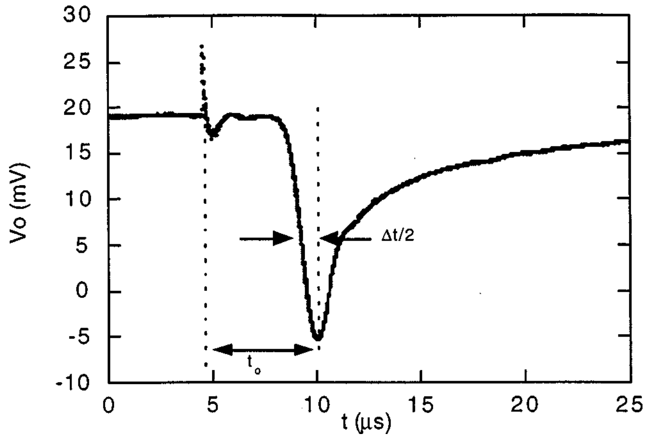

Fig. 14. Waveform observed in a P doped Si wafer ($\rho = 20\,\Omega$ cm) with optical injection.

C. Measurements with Si samples

Despite the small thickness (which strongly reduces the recombination lifetime), we were also able to measure drift mobility on Si P samples obtained by cutting a strip from a 300 μm thick wafer and glueing the end contacts onto vacuum deposited Al pads with conductive epoxy.

A record of one waveform, taken with optical injection on an Si wafer with 20 Ω cm resistivity, is shown in Fig. 14 ($V_S = 38.2$ V, $d = 1.75$ mm, $L = 1.3$ cm, $V_L = 17.7$ V). The measured values $t_0 = 5.24\,\mu$s, $\Delta t/2 = 0.70\,\mu$s yield $\mu = 1137\,\text{cm}^2\,\text{V}^{-1}\,\text{s}^{-1}$ and $D/\mu = 0.033$ V.

Note the long exponential tail of the collector waveform, probably due to excess carriers recombining through ''slow traps.'' As a consequence, the width at half-maximum is here measured as twice the time interval between the half-maximum value in the falling edge and the minimum of the waveform.

The contact resistances of these Si samples can be as high as 30% of the total resistance so that, in computing μ and D/μ, the effective V_S value should be reduced by the same amount with respect to the applied voltage of 38.2 V. This correction increases (by $\approx$30%) the mobility estimation (expected value $\approx$1400 $\text{cm}^2\,\text{V}^{-1}\,\text{s}^{-1}$) and reduces by the same amount the D/μ value (expected value 0.026 V).

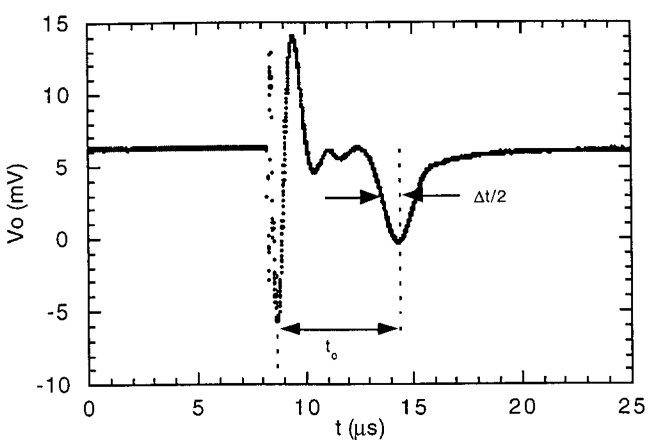

Fig. 15. Waveform observed in a P doped Si wafer ($\rho = 20\,\Omega$ cm) with electrical injection.

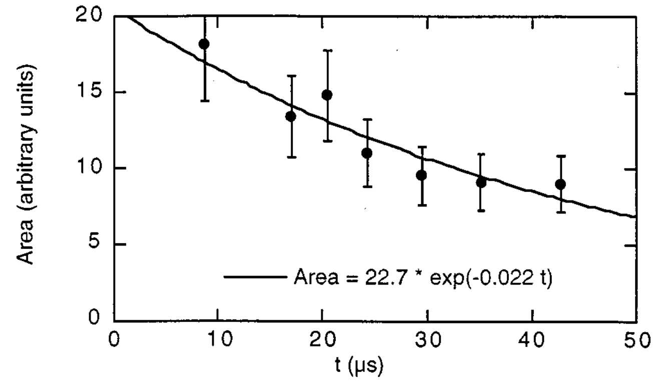

Fig. 16. Recombination lifetime of a P doped Ge sample ($\rho = 16.5\,\Omega$ cm).

One measurement obtained with the same sample and electrical injection is shown in Fig. 15 ($V_S = 38.2$ V, $d = 1.95$ mm, $L = 1.3$ cm, injecting pulse: amplitude $= 13$ V, width 0.3 μs). Here $t_0 = 5.7\,\mu$s and $\Delta t/2 = 0.70\,\mu$s, yielding $\mu = 1164\,\text{cm}^2\,\text{V}^{-1}\,\text{s}^{-1}$ and $D/\mu = 0.031$ V.

V. RECOMBINATION LIFETIME MEASUREMENTS

The recombination lifetime τ_R is required to correct the measured mobility for the effects of diffusion and recombination. This correction is of the order of a few percent for the cases reported in this paper, but it can be more important when the sweep field and/or the drift distance d are very small.

With the Haynes–Shockley apparatus, one can measure τ_R by evaluating the time decay of the excess carriers charge $q(t)$, while keeping constant the injected charge $q(0)$. The value of $q(t)$ is proportional to the area A of the collected pulse, so that measuring A on different waveforms recorded at different times of flight allows us to trace the plot $A(t)$, provided that $q(0)$ is kept constant and that the collector efficiency is not changed.

The last condition is satisfied only if we keep fixed the collector point probe and if the sweep field is constant (the reverse bias of the point contact can be affected by the sweep field).

Therefore, to change the time of flight of the excess carriers, we can only change the position of the emitter. With electrical injection, this does not give a constant $q(0)$ because the injecting efficiency of the point probe emitter is not reproducible.

With optical injection, by changing the position of the optical fiber we still introduce some random modulation in $q(0)$ because the surface conditions, and consequently the number of photons injected into the sample, may vary along the sample, but no systematic changes, related to the time of flight value, are produced.

One measurement obtained with optical injection in Ge P ($\rho \approx 16.5\,\Omega$ cm) is shown in Fig. 16. The data were taken with $L = 3.6$ cm, $V_L = 17.9$ V and $V_S = 24$ V. The estimated lifetime is $\tau_R = (45 \pm 2)\,\mu$s.

VI. CONCLUSIONS

The Haynes–Shockley experiment is a very instructive tool for students, both at the university and college level, to investigate the electrical transport properties in semiconductors, if a suitable apparatus is made available.

We presented here a flexible setup that may be assembled at a modest cost, and that allows the students to obtain accurate measurements without special skills nor semiconductor samples of special doping.

Several copies of the apparatus described here were successfully used in undergraduate physics courses at Padova University, and during training courses for high school physics teachers. The Gerber file providing the PCB layout of the whole circuitry may be requested from the authors by electronic mail: *Torzo@padova.infm.it*, or *Sconza@padova.infm.it*

[1] J. R. Haynes and W. Shockley, ''The mobility and life of injected holes and electrons in germanium,'' Phys. Rev. **81**, 835–843 (1951); **75**, 691 (1949).

[2] A. Sconza and G. Torzo, ''A simple and instructive version of the Haynes–Shockley experiment,'' Eur. J. Phys. **8**, 34–40 (1987).

[3] Here we describe the case of a p-doped sample, where minority carriers are electrons: the case of an n-doped sample can be derived by simply exchanging the role of electrons and holes and the sign of the applied voltages.

[4] The V_s, or *sweep voltage*, is applied for a time of some hundred microseconds and shut off for a time an order of magnitude longer, to prevent sample overheating.

[5] Shyh Wang, *Fundamentals of Semiconductors Theory and Devices Physics* (Prentice–Hall, Englewood Cliffs, NJ, 1989), p. 296.

[6] H. B. Prince, ''Drift mobilities in semiconductors: I germanium,'' Phys. Rev. **92**, 681–687 (1953), and ''Drift mobilities in semiconductors: II silicon,'' *ibid.* **93**, 1204–1206 (1954).

[7] As a point probe we use small embroidery needles (Milward n. 12).

[8] We use the model C86150E of the EG&G, emitting at $\lambda = 905$ nm, cost≈50 US$, recently replaced by PGS1S09, cost≈100 $.

[9] This occurs when the sweep voltage is larger than 30 V and/or the collector is positioned far from the grounded end of the sample.

[10] CP4 is a mixture of 60% nitric acid, 30% acetic acid, and 10% hydrofluoric acid.

[11] J. P. McKelvey, ''Diffusion effects in drift mobility measurements in semiconductors,'' J. Appl. Phys. **27**, 341–343 (1956); also see Ref. 2.

START WITH AN EXAMPLE

If you are going to explain to an average class how to find the distance from a point to a plane, you should first find the distance from $(2, -3, 1)$ to $x-2y-4z+7=0$. After that, the general procedure will be almost obvious. Textbooks used to be written that way. It is a good general principle that, if you have made your presentation twice as concrete as you think you should, you have made it at most half as concrete as you ought to.

Remember that *you* have been associating with mathematicians for years and years. By this time you probably not only think like a mathematician but imagine that everybody thinks like a mathematician. Any nonmathematician can tell you differently.

Ralph P. Boas, Jr., ''Can We Make Mathematics Intelligible?,'' in *Lion Hunting & Other Mathematical Pursuits*, edited by Gerald L. Alexanderson and Dale H. Mugler (Mathematical Association of America, Washington, 1995), p. 231.