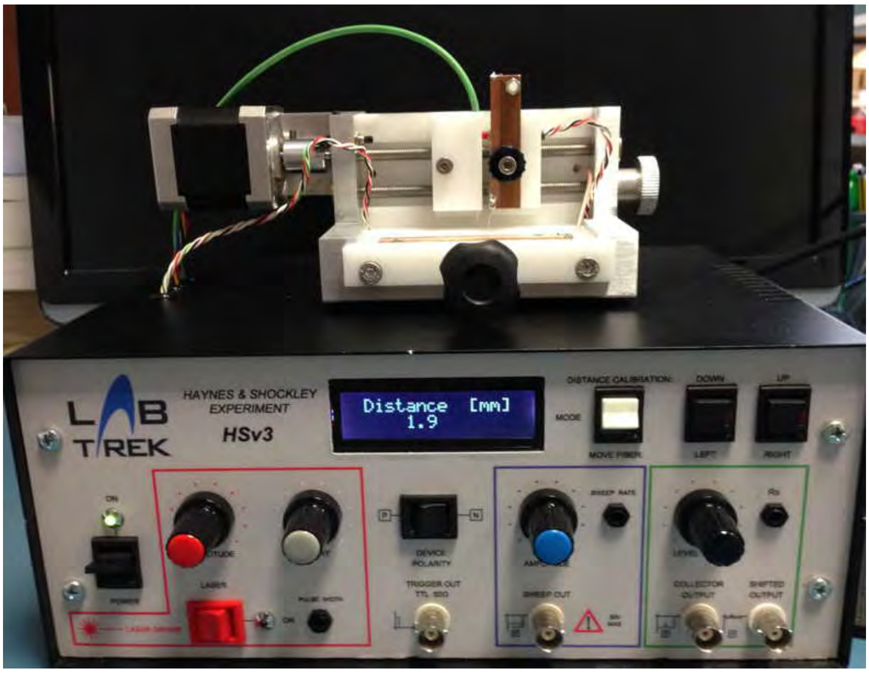
The Haynes – Shockley experiment. Version 3



Introduction

The experiment proposed in 1949 by J. R. Haynes and W. Shockley[1] to measure the drift mobility of electrons and holes in semiconductors is conceptually simple. The main difficulties are in the sample preparation, in the charge injection and in the signal detection. It is an experiment with great didactical value, because it allows a direct investigation of the drift velocity, of the diffusion process and of the recombination of excess charge carriers. In the version here described the excess carriers are optically injected (using internal photoelectric effect) avoiding the need of a reliable point-contact emitter.

[1] J.R. Haynes and W. Shockley, "*Investigation of holes injection in transistor action*" Phys. Rev. 75, 691 (1949) and Phys. Rev. 81, 835 (1951). It was the first experiment to measure directly the drift velocity, and thus mobility, of minority carriers. Previously the drift velocity was determined with the Hall effect, which was an indirect method whose results could not be easily interpreted. See also references 3-5.

1. The original experiment of Haynes and Shockley.

In the original H-S experiment an electric field is created along a small bar of a doped semiconductor (cut from a single crystal ingot) by applying an external voltage across the bar ends. Then a short pulse of excess minority charge carriers is injected into the sample and it is swept along the bar by the electric field. By detecting and analyzing the excess-charge pulse during its travel (before it reaches the bar end, and before it dies out due to recombination processes), the drift velocity, the diffusion constant and the lifetime may be calculated.

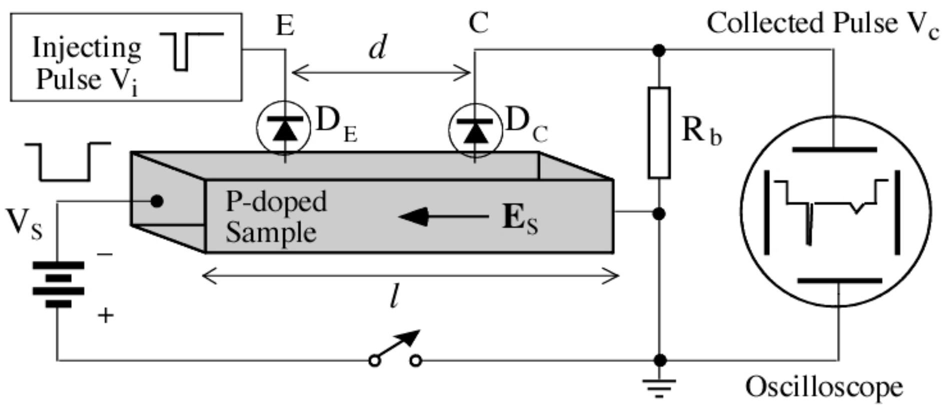


Figure 1: Block diagram of the original H-S experiment

The block diagram of the original H-S experiment is shown in Fig.1.

As an example, let us consider a P-doped semiconductor bar, of length l , with ohmic contacts soldered at both ends

Inside the sample an electric field E_s (named *sweep field* $E_s \leq 10$V/cm) is temporarily produced by a pulsed generator, sketched in Figure 1 as a battery in series with a switch. Two point contacts (electrodes E and C) are made by two metal needles separated by a distance d . The point contacts are (partially) rectifying and therefore they are drawn as diodes in figure 1 (see Appendix 1).

By applying to the electrode E (emitter) a short negative pulse V_I with amplitude large enough to *forward* bias the diode D_E, electrons will be injected into the crystal region underlying the emitter. This electron pulse will drift, under the electric field action, with velocity v_d, and after some time t it will reach the region underlying the electrode C (collector).

The diode D_C is reverse biased (its "cathode" is grounded through the resistance R and the "anode" is inside the crystal at negative potential) and therefore only the weak inverse current normally flows across R (electrons from the P semiconductor to the metal). When the excess electron pulse reaches the point contact C, the minority charge carrier density is locally increased, thus increasing the inverse current and producing a voltage drop across the resistance R.

On the oscilloscope screen we may observe a first short negative pulse, with amplitude comparable to that of the injection pulse V_I and, after some delay t, a second negative pulse, wider and much smaller than the first one. An example of the collected signal in a *N-doped* Ge sample, with *positive* injecting and sweep pulses is shown in figure 2 (here the excess injected carriers are holes, not electrons).

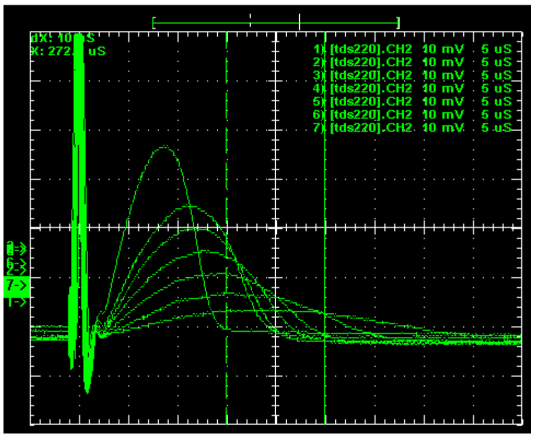


Figure 2: Signals collected in Ge-N using point-contact injection

The first peak is simultaneous with the injection pulse: it is due to the electromagnetic signal propagating across the sample (at the light speed, as in any conductor). The second pulse corresponds to the excess-charge distribution passing under the collector contact: its shape is approximately Gaussian and its amplitude and width are determined by diffusion and recombination processes.

An analytical interpretation of the pulse shape, based on the solution of the time dependent diffusion equation, may be found in reference 1. A short, qualitative, explanation, in the case of P-doped sample, is the following.

Immediately after the injection of the excess electron, within a time of the order of the *dielectric relaxation time* (ε/σ is typically 10^{-12} s, where ε is the dielectric constant, and σ the conductivity), an excess hole concentration neutralizes the excess electrons in the injection region. The local increase of charge carrier density drifts towards the collector with an effective mobility $\mu^* = \dfrac{\mu_e \mu_h (p-n)}{\mu_e n + \mu_h p}$ that, due to the P-doping ($p \gg n$), reduces to $\mu^* \approx \mu_e$ i.e. to the *minority charge mobility* (electrons).

When this excess carrier "cloud" reaches the collector C the point contact collects the minority charges, building across the resistance R a negative voltage pulse (with an approximately Gaussian shape). The actual pulse shape depends on the drift time t, on the covered distance d and on the drift velocity $\mu^* E_s$.

The injected electrons in fact, while drifting towards the collector, diffuse broadening their spatial distribution, so that the width of the collected pulse increases with the time of flight t.
Moreover the electrons recombine with holes so that their number decreases exponentially with time as:

$$N(t) = N_0 \exp(-t/\tau) \qquad [1]$$

where τ is the *lifetime of the excess charge carriers*.

2. Information that can be extracted from the pulse shape and position.

The measurement of the *time of flight t*. and of the distance d between the two point contacts gives the drift velocity v_d:

$$v_d = d/t \qquad [2].$$

The value of the amplitude of the sweep pulse V_S, which may be read on the front panel display, and of the sample length L give the value of the sweep field $E_S = V_S/L$ and therefore of the electron *mobility* μ :

$$\mu = |v_d|/|E_S| = (d\,L) / (t\,V_S) \qquad [3].$$

The measurement of the *pulse width at half-height* Δt gives the *diffusion constant D*, through the relation:

$$(v_d\,\Delta t)^2 = 16 \ln 2\, D\, t \qquad [4]$$

(valid when the injection pulse width is negligible with respect to the time of flight t and with respect to the collected pulse width Δt). As explained in the Appendix1, the diffusion produces a Gaussian broadening of the injected narrow peak, resulting in a pulse width at half-height $\Delta x = \sqrt{16 \ln(2)\, D t}$ that drifts with a velocity v_d : it takes therefore the time $\Delta t = \Delta x / v_d$ to cross the collector position .

The ratio D/μ obeys the Einstein relation: $D/\mu = kT/e$, (where k is the Boltzmann constant, T the absolute temperature and e the elementary charge) that gives at T=300K the value $D/\mu = 0.026$ volt.
From relations (4) and (2) by replacing v_d^2 with $(d/t\ \mu E_S)$ we obtain:

$$D/\mu = \frac{V_S d}{11.08\ l} (\Delta t/t)^2 \qquad (5)$$

By measuring the collected pulse *area A* we may evaluate the *lifetime* τ of the excess carriers;

$$A = \int_0^\infty V_c(t')dt' = R \int_0^\infty \Delta i(t')dt' \propto R\, e\, \eta\, N,$$

where $\Delta i(t') = V_C(t')/R$ is the increase of the collector inverse current, $V_C(t')$ is the pulse height, η is the collector efficiency for minority carriers, e is the elementary charge and N the number of minority carriers at the collector point contact.
As N decreases with time according to relation [1] we get:

$$A(t) = A_0 \exp(-t/\tau) \qquad [5].$$

Similar measurements may be carried out for holes in N-doped crystal by using positive injecting and sweeping pulses (the diodes polarity is reversed with respect to that shown in figure 1).

3. Setup with optical injection.

The excess charges may be generated by a light pulse (by exploiting the internal photoelectric effect) e.g. using a light beam, produced by a LASER diode, and the emitted light beam is guided by an optical fiber with one end replacing the emitter point contact.
This setup greatly simplifies the experimental procedure: by using only one point contact (the collector) we avoid the need of re-adjusting the injecting pulse voltage every time that the sweep voltage or the emitter position in changed [2], and moreover we obtain a higher excess charge density in a shorter time (the light pulse width may be adjusted in the range 20 - 200 ns), thus achieving a better resolution in the measurement of the time of flight.

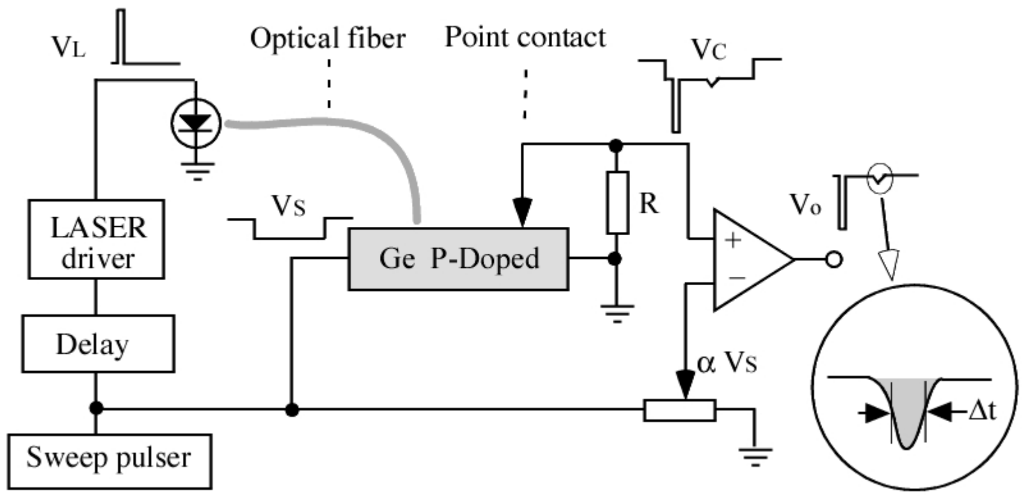


Figure 3: Block diagram for optical injection and point-contact collector

[2] As explained in details in reference 5

The setup, schematically shown in figure 3, is made of:

a) Bar-shaped sample with two ohmic contacts at the ends

b) Sample holder with two gliders (one for the optical fiber and one for the point-contact collector)

c) Double pulser for the sweep voltage and for the laser-driving pulse, with a differential amplifier subtracting the sweep voltage from the collector signal

A digital oscilloscope is obviously needed to detect and record the collector pulse (suggested a minimum bandwidth of 60 MHz).

Particularly useful is an oscilloscope including the ability of *averaging many pulses* (to increase the signal to noise ratio), and an *interface* (through USB or GPIB port) to download the recorded pulse shape to Personal Computer, for off-line analysis.

3.1. The sample

The semiconductor sample is a thin bar (approx. 3x3x20 mm) cut from a single crystal ingot with ohmic contacts on the two ends. Germanium is a particularly easy material because nearly-ohmic contacts may be easily obtained by soft (tin-lead alloy) soldering (better with the aid of a drop of deoxidizing solution). The sample surface should be previously wet-lapped by very fine emery paper (#2000) in water on a flat plane until a mirror surface is obtained, then polished with wet alumina powder. The sample should then etched shortly (1 minute) with CP4 [3] and rinsed in water.

3.2. Sample holder

The sample is fixed on an insulating holder by a spring-loaded clamp. Its axis is aligned with the two threaded axes that drive two gliders (figure 4) which carry the optical fiber (glider 1) and the collector point-contact (glider 2), respectively.

[3] CP4 is a toxic mixture of nitric acid (60%), acetic acid (30%) and hydrofluoric acid (10%). Avoid contact with skin and avoid breathing vapors.

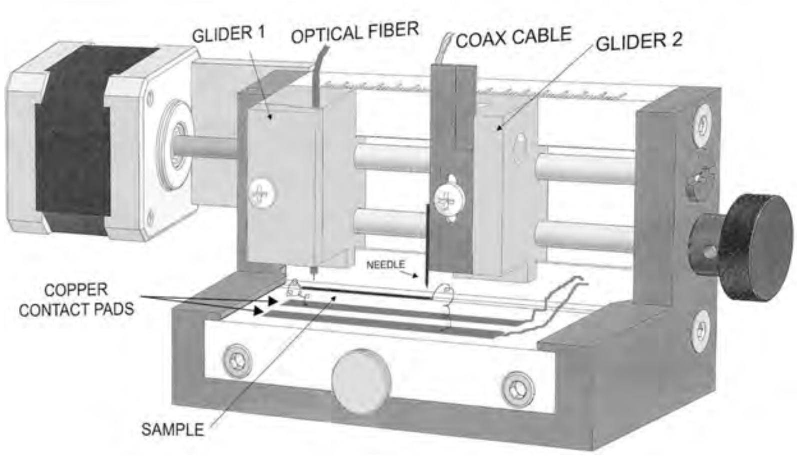


Figure 4: Sample holder with two gliders carrying the fiber and the needle

The spring-loaded point contact [4] may be vertically shifted (by releasing the front screw) to adjust the pressure on the point-contact. Glider 2 may be moved by manually turning the aluminum handle. Before moving glider 2 *the point should be risen* to avoid damaging the needle apex and the crystal surface.

The sample is held inside spring-loaded vice, that can be horizontally displaced orthogonally to the sample major axis. To *loosen* the vice: rotate CLOCKWISE the front handle.

One end of the optical fiber (diameter 200 μm) is coupled to the laser diode and the other end is vertically blocked into the glider 1 so that it may slide along the sample major axis. The step-motor coupled to the glider 1 is acted by pressing the LEFT and RIGHT buttons on the front panel (when the switch MODE is in the position MOVE FIBER).

Two micro switches stop the motor when the glider reaches the left or the right limits.

The fiber end should be placed approximately at 1 mm distance above the sample surface. The *invisible* light beam (the 905 nm laser wavelength is in the IR region) should be centered on the sample because the electron-hole pairs generated close to the lateral surfaces are affected by faster recombination due to the surface defects that act as recombination traps.

[4] Model SPR-1W-2/SPR-1W-2M produced by Everett Charles Technologies

The fiber end is delicate: do not allow it to hit hard walls. Do not pull strongly the fiber: it is coupled to the power laser output by a sensible adjustment, and mechanical stresses may produce optical mismatching.

The cables carrying the sweep signal and the collector signal are mini-coax cables (ground shielded to reduce pick-up noise).

The sweep signal is supplied to a pair of copper contact-pads to make easier the replacement of the sample, which has two wires soldered with ohmic contacts at the ends.

The fiber-collector distance is read on the front-panel LCD screen. The distance is calculated by a software routine[5] that is written into the Arduino™ microprocessor that drives the step motor, using the signal of the micro switch placed on the glider 2.

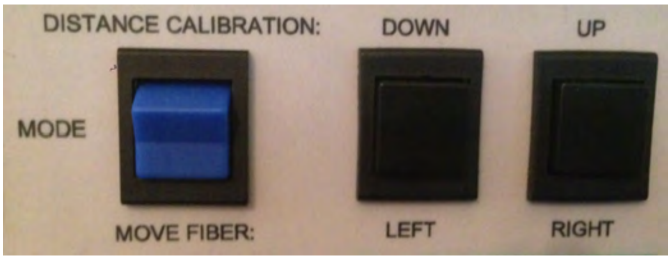


Figure 5: Distance calibration Mode-Switch and Control-Buttons

The four-steps calibration procedure is the following (see figure 5).

1) With the MODE switch on MOVE FIBER position: press RIGHT button to right-move the glider 1 until its stops against glider 2; read the distance value displayed on the LCD screen;

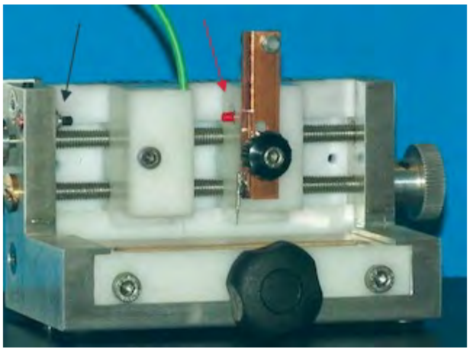
2) compare the reading with the actual fiber-point distance that may be evaluated using a caliper (this distance is obviously the minimum distance that may be used in the experiment);

3) if the values do not match, turn the MODE switch into position DISTANCE CALIBRATION and use the DOWN or UP buttons to change the displayed distance reading (in millimeters) until it matches the measured value;

[5] The routine may be modified by connecting a PC to the USB port in the rear panel, and by using the standard Arduino application. WARNING: before connecting the PC to USB port, you must switch-off the Haynes-Shockley device (power switch = OFF).

4) when the correct value is displayed, switch back the MODE switch into MOVE FIBER position and use the LEFT (or RIGHT) button to place the fiber at the desired distance.

Some attention must be paid to the limit-switch that stops the motor when the glider reaches the minimum fiber-tip distance. It is inserted into a hole and its position may be regulated and then blocked by a fixing screw so that the switch-button is engaged BEFORE the two gliders come into mechanical contact.



With reference to the figure above: the limit switch marked by red arrow provides the motor stop. the CALIBRATE mode is active only when the limit switch is closed. However if you have manually moved the right glider when it was in contact with the left glider, you may have forced (moved BACK) the limit switch, so that it cannot work properly. In this case you must restore the original setting of the limit switch by moving it FORWARD (after loosing the fixing screw on top). The proper setting should stop the motor BEFORE a mechanical contact between the two gliders occur.

The LCD screen displays the 3 working parameters (fiber-collector distance **d** in mm, sweep voltage **VS** and laser bias voltage **VL** in volt).

Warning !!! Before connecting to the PC the USB port on the rear panel, you must switch-off the Haynes-Shockley device (power switch = OFF), because there is a ground-conflict : the Arduino ground (metal shield of USB port) is internally connected to the floating ground of the sweep voltage power supply.

The complete routine code may be found in the Appendix 5

3.3. Double pulser

The sweeping field cannot be continuously applied to the sample, in order to avoid self-heating. Therefore the sweep voltage must be provided by an adjustable-amplitude pulser ($V_{max} \approx 50V$), with a pulse width of some hundreds microseconds and repetition rate in the range 30 - 50 Hz[6]. A second pulser, synchronized with the first one, must switch-on the laser diode for electron-hole pairs injection. The second pulse is produced with some (adjustable) delay with respect to the first one, to avoid interference with the transient noise due to the conductivity change induced, at the sweep-pulse onset, when the end contacts are not perfectly ohmic.

Working with N-type samples requires positive sweep pulses, while for P-type samples the pulse must be negative. This feature is achieved using a floating power supply electronically switched, with polarity chosen through the DEVICE POLARITY switch on the front panel (switch SW2 in figure 6).

3.3.1. Sweep pulse generator

The V_S pulse generator is driven by an astable multivibrator obtained from a Timer NE555 in the free running configuration (CLOCK), through by a 2^6-divider, so that the pulse duty-cycle is always 1/64. The pulse width τ_s may be adjusted through a potentiometer (*sweep rate* control, accessible in the front panel), which regulates the clock period, in the range 300-500 μs.

The output voltage Vs is obtained by driving, through a photo coupler, a power MOSFET switch which connects the floating power supply to the sample. The Vs output amplitude (in the range 5 - 50V) is adjusted by the potentiometer SWEEP AMPLITUDE (P3 in figure 6) regulating the floating power supply.

[6] The ratio between the power dissipated with pulsed sweep voltage and the power dissipated with the same d.c. bias voltage is approximately equal to the duty cycle (ratio between ON and OFF times).

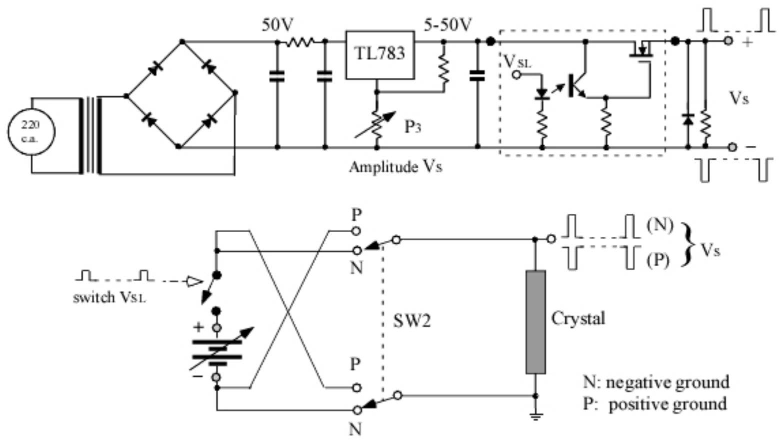


Figure 6: Block diagram of the pulse generator for sweeping voltage Vs

The power W dissipated by the crystal can be calculated knowing its resistance R through the relation : $W=(V_S)^2/64R$.

3.3.2. Diode laser pulse generator

The potentiometer DELAY, on the front panel, adjusts the laser pulse delay (by varying the time constant in a RC filter which controls the triggering of a TTL monostable pulser). The TTL signal is available on the TRIGGER OUT port on the front panel to allow driving the oscilloscope external trigger. This TTL signal has the rising edge synchronous with the sweep voltage onset and the falling edge synchronous with the laser pulse onset. Therefore the user may choose the trigger type simply by selecting on the oscilloscope the rising or falling edge.

The current is fed to the diode laser is by discharging (through a power MOSFET switch) a capacitor-bank that are charged by a floating power supply that can be regulated in the range 5-25V using the potentiometer AMPLITUDE on the front panel. The current flowing through the diode laser (and therefore the light pulse intensity, i.e. the number of emitted photons) is proportional to the voltage of the capacitor-bank.

The laser pulse width may also be adjusted in the range 20-200 ns, using a screwdriver to adjust the trimmer PULSE WIDTH on the front panel: the number of photons is only roughly proportional to the light pulse width.

The diode laser is a 905D1S06C, wavelength: 905 ± 10 nm, maximum current: 15 A, peak power: 13 W, maximum pulse duration: 200 ns, maximum repetition rate: 40 Hz.

For laser safety infos see chapter 5.

3.3.3. Collector signal detector

In order to detect the collector signal V_C on the oscilloscope a sensitivity of some mV and a bandwidth of at least 60 MHz is required.

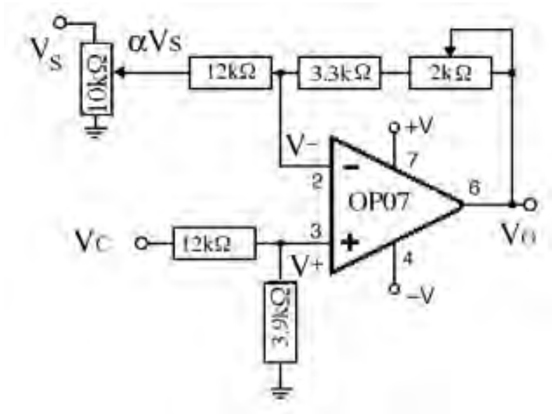


Figure 7: Differential amplifier

Moreover the V_C signal must be first processed by a differential amplifier (e 7) to subtract an adjustable fraction V*= αV_S of the sweep voltage [7], so that the oscilloscope amplifies only the collected pulse (see figure 8).

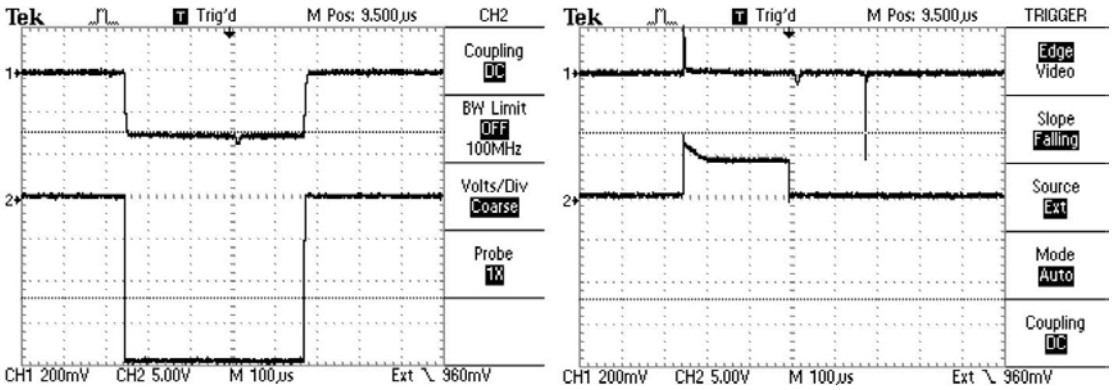


Figure 8: Left: COLLECTOR OUTPUT (trace 1) and SWEEP OUT (trace 2)
Right: SHIFTED OUTPUT (trace 1) and TRIGGER OUT(trace 2)

Both the input (V_C) and the output (V_C - αV_S) signals of the differential amplifier are available at two BNC ports on the front panel (COLLECTOR OUT and SHIFTED OUT, respectively).

[7] The fraction α is given by the relation $\alpha = x_c/l$, where x_c is the collector to ground-contact distance and l is the sample length.

4. Data collection ad analysis

The amplitude of the collected pulse depends on the cleanliness of the sample surface.
In fact in small size crystals the surface recombination velocity of charge carriers is proportional to the density of lattice defects due to the cut and inversely proportional to the accuracy of the surface lapping.
Mostly important is the point contact: when the signal appears noisy on the oscilloscope screen, the position of the contact should be changed, or it may be useful to gently tap with a finger onto the sample holder to condition the contact between the probe apex and the sample surface, or it might be necessary to re-sharpen the tip using fine emery paper.

4.1. Evaluation of the the point-contact behaviour

The rear panel offers two BNC outputs, marked Ax and Y, and a 3-position switch (H&S, D, R). By connecting the two channels of an oscilloscope to these BNC outputs and setting the scope into the X-Y mode (X output connected to channel 1 and Y output connected to channel 2).
As shown in figure 9, setting the switch to position D feeds the point contact with a 10 V a.c. signal in series with 10 k resistor ; X output monitors the voltage across the contact, while Y output monitors the voltage across the resistor (= current).

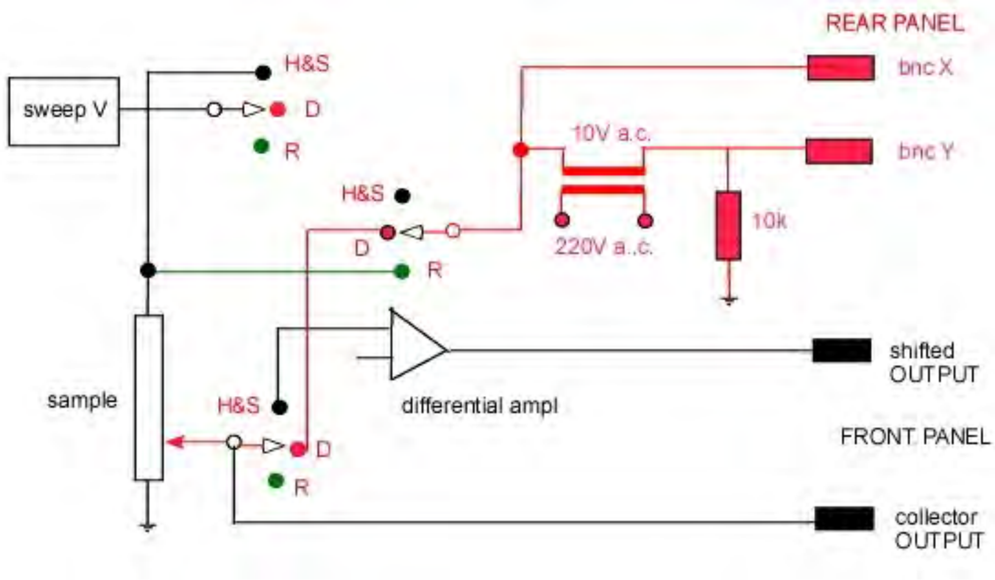
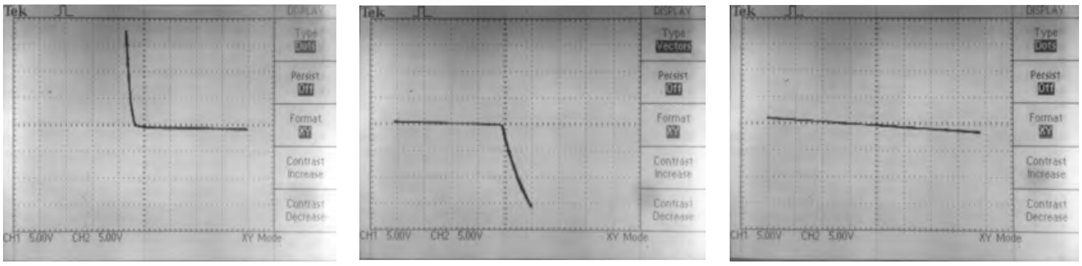


Figure 9: Diagram of point contact test circuit

By selecting the D position for the 3-way switch, you see on the scope screen the I-V characterisctics for the point contact diode. By selecting the R position you verify the ohmic behaviour of the sample end-contacts.

Examples of I-V curves are shown in figure 10.



(1) (2) (3)

Figure 10: I-V curves ; (1) D position P-doped sample, (2) D position N-doped sample (3) R position

Be sure to select the H&S position when performing measurements H-S !

Examples of pulse for excess minority electrons (P-doped samples) and of injeted minority holes (N-doped samples) are shown in Figure 11.

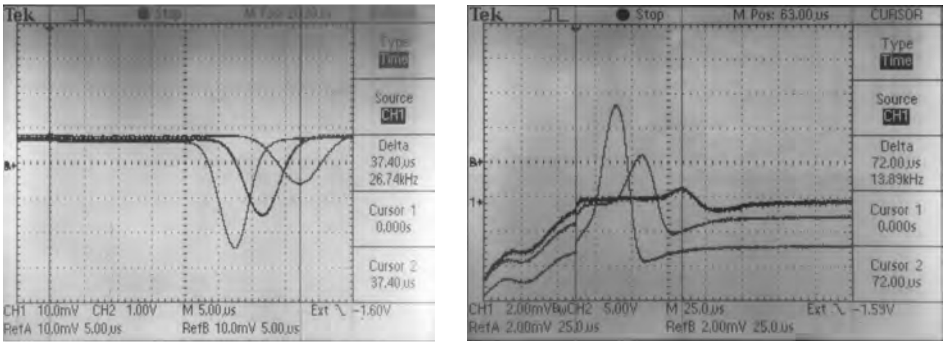


Figure 11: examples of detected pulses in P-doped and N-doped samples

4.2. Measurement of the time of flight *t*

The time of flight is defined as the delay *t* of the collected pulse with respect to trigger time [8] . When measuring at constant sweeping field and at constant flight distance *d*, the value of *t* should be constant, i.e. not dependent on the intensity of the light pulse.

However when the injected charge density becomes too high[9] the observed value of *t* starts to increase (figure 12).

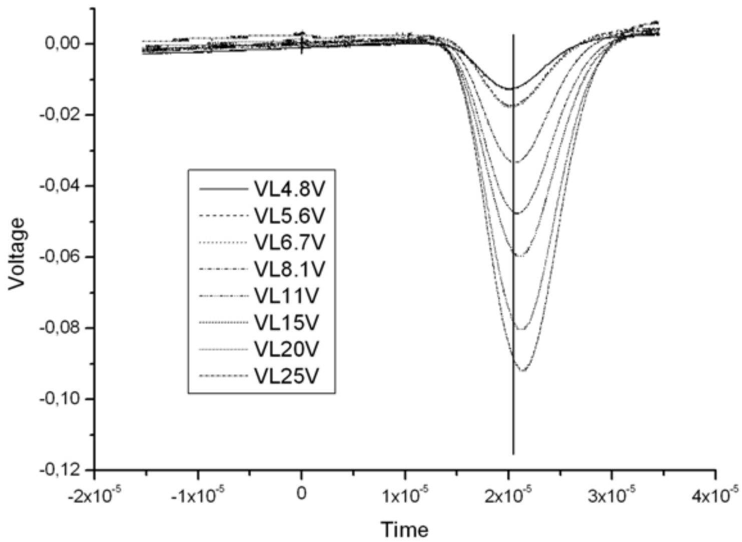


Figure 12: Pulses collected for increasing values of the laser bias voltage V_L , at constant *d*=5mm and constant sweep field E_S=6V/cm.

Once determined the maximum usable value of the injecting pulse intensity, one can proceed measuring the dependence of the *time of flight* on the *sweep voltage V_S*, for a given flight distance *d* (Figure 13).

[8] Note that the width of the injecting pulse, in the range 2-200ns, may be assumed negligible

[9] Note that the injected charge density grows either by increasing the voltage VL on the capacitor bank (AMPLITUDE) or by increasing light PULSE WIDTH.

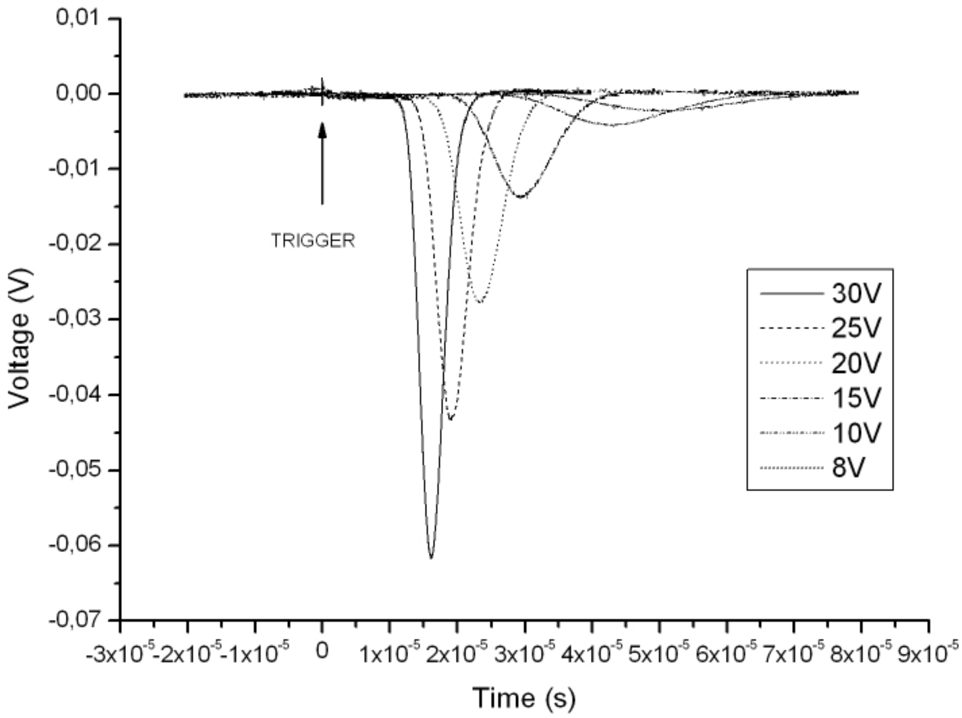


Figure 13: Set of pulses collected at constant *d*=3.5mm, by varying the sweeping voltage V_S.

From the data reported in figure 13 one may calculate the values reported in Table I. The values of pulse area A and of the pulse width (at half height) Δt were obtained through a Gaussian interpolation (see Appendix 4).

V_s (V)	t (μs)	Δt (μs))	A(Vμs)	E_s (V/cm)	μ(cm^2/Vs)	ln(A)
8	51.24	18.11	50.83	2.286	4355	3.928
10	43.67	15.17	78.19	2.857	4087	4.359
15	29.80	8.550	146.5	4.286	3993	4.987
20	23.64	6.057	210.3	5.714	3775	5.349
25	19.36	4.627	250.9	7.143	3688	5.525
30	16.30	3.620	276.5	8.571	3650	5.622

Table I: measurements obtained at constant distance *d*=0.35 cm

4.3. Evaluation of the recombination lifetime

In a semi logarithmic plot of the pulse areas versus time (figure 14) the slope gives the reciprocal of the recombination lifetime τ.

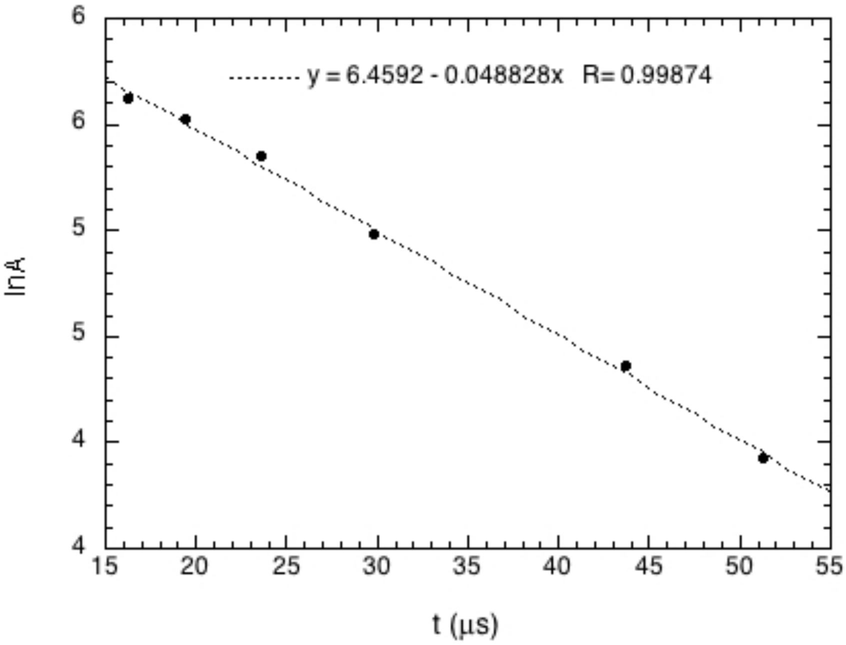


Figure 14: ln(A) vs. *t*

4.4. A first evaluation of the mobility μ

The mobility values calculated for constant flight distance with various sweep voltages show a large dispersion [the average gives (3924±270) $cm^2V^{-1}s^{-1}$] but also a systematic dependence on the sweep voltage (figure 15) . This effect is explained in section 4.7.

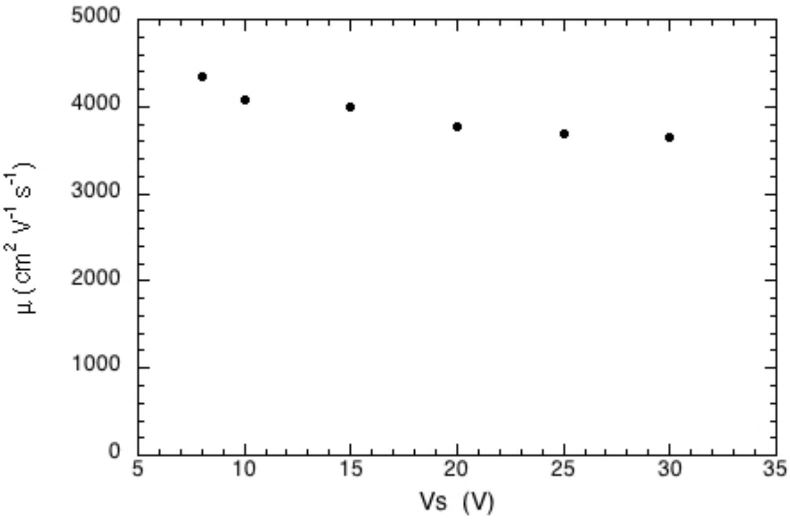


Figure 15 : Mobility values calculated for d=0.51 cm an various V_S values

4.5. Mobility measurements at constant sweeping field

More measurements of t may be made while keeping constant the sweeping field and changing the flight distance d (by moving the glider holding the fiber while keeping fixed the collector[10]).

An example of such measurements is shown in Table II and in Figure16.

d (cm)	t (μs)	μ (cm^2/Vs)	Δt (um)	$(d\ \Delta t)^2$	t^3
1.24	98	4221	25.1	9.62e-10	9.41e-13
1.05	84	4187	27.0	8.02e-10	5.93e-13
0.95	80	3978	25.6	5.91e-10	5.12e-13
0.85	69	4126	24.1	4.19e-10	3.29e-13
0.7	58	4043	22.8	2.54e-10	1.95e-13
0.6	50	4020	22.3	1.79e-10	1.25e-13
0.5	41	4085	17.7	7.81e-11	6.89e-14
0.4	33	4060	16.3	4.24e-11	3.59e-14

Table II: Measurements obtained at constant Vs=10 V

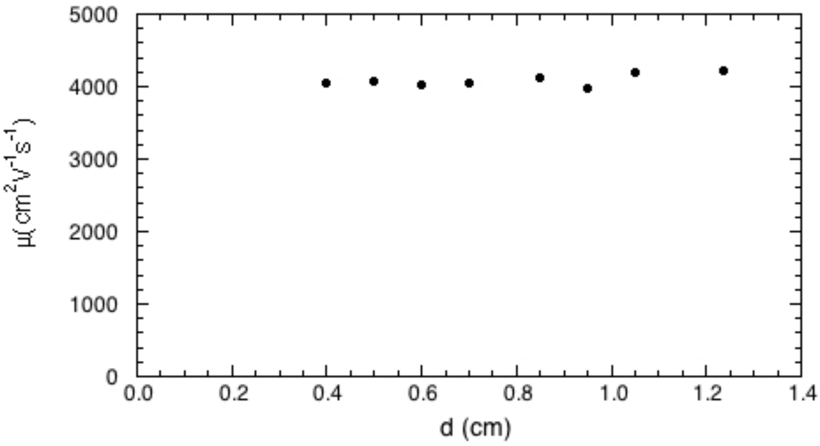


Figure 16: Mobility values calculated for Vs=10V and for different values of d

[10] This warrants a constant efficiency of the point-contact collector, that turns out useful when evaluating the pulse area decay

4.6. Evaluation of the diffusion constant *D*

The diffusion constant *D* may be calculated through the relation [4] $(v_d \Delta t)^2 = 16 \ln 2\, D\, t$, or, using the definition $v_d = d/t$:

$$(d\,\Delta t)^2 / 16\ln 2 = D\, t^3 \qquad [6]$$

Relation [6] shows that a plot of the square of the product $(d\,\Delta t)$ divided by 16ln2, as a function of the cube of the time of flight t^3 , should be fitted by a straight line with slope *D* (figure 17). This kind of plot should be made using data taken *with different values* of the flight distance *d*, to avoid the large systematic error introduced by the large uncertainty on the single *d* value.

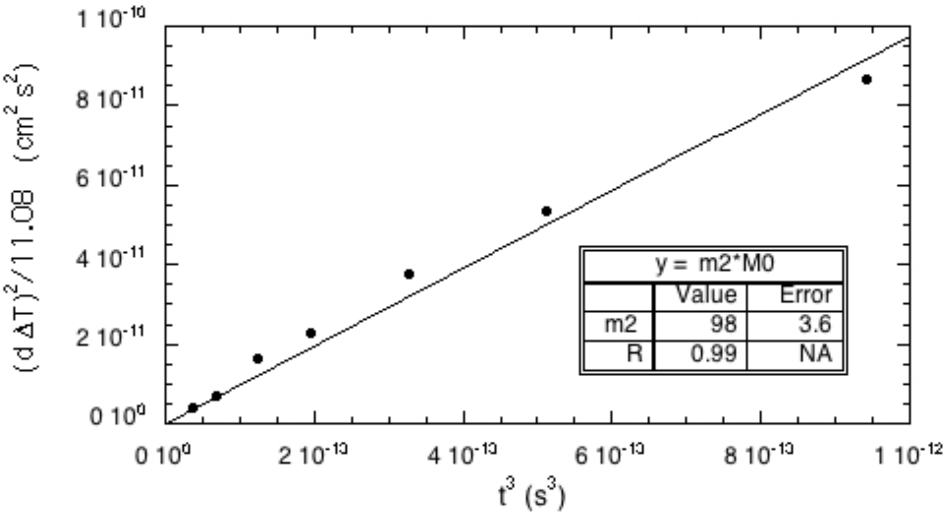


Figure 17: Plot of $(d\,\Delta t)^2$ as a function of t^3

In the plot of figure 17 the proportionality predicted by the model is well obeyed, giving for the electron diffusion constant the value $D_e = (98 \pm 4)$ cm²/s.

An alternative way of evaluating *D* is through the ratio D/μ with the formula :

$$D/\mu = (V_S\, d/16 \ln 2\, l)\,(\Delta t/t)^2 \qquad [7]$$

obtained from relation [4] with the substitution $v_d^2 \rightarrow (d/t)\mu E_S$.

The calculated D/μ value may be compared with the value predicted by the Einstein relation: $D/\mu = kT/e = 0.026$ Volt (at T=300K).

The data reported in Table 1 give an average value $D/\mu=(0.0258\pm0.0031)$ V in good agreement with the predicted value .

4.7. Systematic error in the measurements of μ

The systematic dependence of the mobility on the sweep field, observed in sect. 4.5, is due to diffusion and recombination of the excess carriers, effects that becomes important at small V_S values (for longer values of time of flight the pulse broadens and its amplitude decreases).

A qualitative explanation of this effect is the following: assuming a very large lifetime for the excess carriers, we should observe at the collector (due to diffusion) a broad peak even with zero sweep field, which means *infinite mobility*. In fact with zero drift velocity and finite diffusion, a first increase of local carrier density should be observed at the collector, followed by a decrease (uniform distribution).

A quantitative analysis was made by J.P McKelvey[11], who obtained the correction formula:

$$\mu_{corr} = \mu\,(\sqrt{1 + x^2} - x) \qquad [9]$$

where the parameter x is:

$$x = \frac{2kTl}{eV_S d}(t/\tau + 1/2) \qquad [10].$$

Assuming τ=20 μs, value obtained from the pulse decay measurements reported in figure 14, the μ_{corr} values result much less scattered around the average value even for low V_S values (Figure 18): we get μ_{corr}(3678±77) cm^{2}V^{-1}s^{-1}.

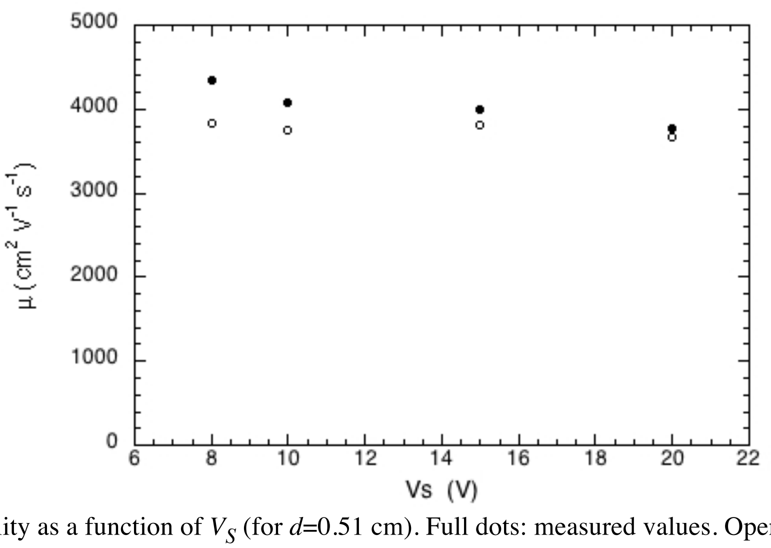


Figure 18 : Mobility as a function of V_S (for d=0.51 cm). Full dots: measured values. Open dots: values corrected using relations (9-10)

[11] see ref. 2

4.8. The mobility temperature dependence

If the pulse width is long (duty cycle > 10%) and the applied voltage is high (>30 V) the sample is heated by Joule effect and the drift velocity decreases.

The mobility depends on temperature as μ=cost $T^{-\alpha}$, and therefore $\Delta\mu(T)/\mu \approx -\alpha\, \Delta T/T$.

In a p-doped Ge sample where $\alpha \approx 2.3$, the electron mobility (μ_e=3900 cm^{2}V^{-1}s^{-1}at $T \approx 300$ K) decreases by the amount $\Delta\mu_e = \alpha\, \mu_e(\Delta T/300) \approx 30\Delta T$ cm^{2}V^{-1}s^{-1}.

5. Laser safety

The Haynes-Shockley apparatus includes a diode laser Class 3B (model 905D1S06C, wavelength: 905 ± 10 nm) which is potentially dangerous, if unproperly handled.

This diode laser is safely coupled to an optical fiber (model JTFLH2002300500 MOLEX 200um, 1 m long)

The actual max peak current used in our device < 4A (regulated through the voltage set by potentiometric control on the front panel)

The maximum pulse duration: used in our device < 200 ns (regulated through a potentiometric control on the front panel)

The maximum repetition rate used in our device < 50 Hz (regulated through a potentiometric control on the front panel).

The power attenuation for diode-fiber coupling plus attenuation along the fiber is >100

Because the maximum pulse duration is less than 200 ns, while the maximum repetition rate is 50 Hz, the overall attenuation of the power output is about 10.000.000 at the maximum allowed peak current (15 A) and about 40.000.000 at our maximum peak current (4 A).

Therefore the effective power output is less than 2.5 uW (microWatt), which set the laser class**: Laser Class 1**

The fiber is kept in place in our apparatus (pointing to the sample) so that there is no possible stray light aiming at the user.

Therefore **no safety glasses are required.**

To replace the fiber the user must send the device back to producer because laser-fiber coupling must be performed in the factory.

Appendix 1 : Metal-semiconductor contact (*ref. 1*)

The free surface of a semiconductor is always made of a thin oxide layer (1-2 nm). The different lattice parameter of the oxide creates defects in the crystal lattice and therefore introduces surface energy states (*traps*) within the band gap, both for holes and electrons.

In a metal-oxide-semiconductor contact for N-doped sample, the surface states capture free electrons producing a double layer of charges (negative at surface and positive inside the crystal, bound to donor atoms). This produces a potential barrier similar to that of a PN junction, with the difference that the negative charges are only at the surface layer while the positive charges are distributed in a region extending inside the crystal.

The potential barrier increases if a negative external voltage is applied to the metal, and no current due to majority carrier (electrons) crosses the junction. Vice versa with a positive voltage applied to the metal the potential barrier decreases and the majority carriers diffuse across the junction. The situation corresponds to a diode with the anode on the metal side and the cathode on the semiconductor side.

In a metal-oxide-semiconductor contact for P-doped sample,, the surface states capture holes inside the semiconductor and the double layer polarity is reversed.

Appendix 2: The excess carrier diffusion process

The excess carriers are locally injected and they diffuse from the region with higher carrier density to regions with lower carrier density.

Without externally applied electric field, for small perturbations, the charge conservation equation may be written $\boldsymbol{j} = -D\, \mathbf{grad}\, n$, where $\boldsymbol{j}$ is the flux of carrier [cm^{-2} s^{-1})], n the carrier density (cm^{-3}) and D the diffusion constant (cm^2 s^{-1}).

By solving the Boltzmann transport equation we get: $D=\langle v\rangle\lambda/3$, where $\langle v\rangle=\sqrt{3kT/m}$ is the mean thermal carrier velocity and λ the mean free path. Writing $\langle v\rangle \approx\lambda/t_c$, where t_c is the mean collision time, we obtain $D\approx kTt_c/m$.

Recalling the mobility definition within the Drude model: $\mu=et_c/m$, we get the Einstein relation:

$$D/\mu = kT/e$$

The continuity equation for minority carriers, in presence of carrier generation, recombination and diffusion, may be written (with the assumption of weak perturbation of the equilibrium carrier density n_o) along the x-axis as:

$$\partial n/\partial t = -(1/e)\, \partial J/\partial x - n/\tau + (G)$$

where G is the generation rate (e.g. optical injection), τ the carrier lifetime, and J the current density:

$$J = -e\, D\partial n/\partial x + e\, \mu\, n\, E_x$$

Which is the sum of a diffusion term (proportional to the density gradient along x) and of a drift term (proportional to the electric field E_x component along x).

By solving the continuity equation in the case of zero external field (E_x =0), with N_o charges injection at t=0 in x=0, the result is :

$$n(x,t) = (N_o /\sqrt{(4\pi Dt)}) \exp\{-t/\tau\} \exp\{-x^2/(4Dt)\}$$

whose width at half height Δx is:

$$(\Delta x)^2=16 \ln 2\, D\, t = 11.08\, D\, t.$$

Appendix 3: Pulse shape recording and analysis

The pulse shape displayed on the oscilloscope screen may be recorded in the Personal Computer memory if the oscilloscope is equipped with a serial interface.

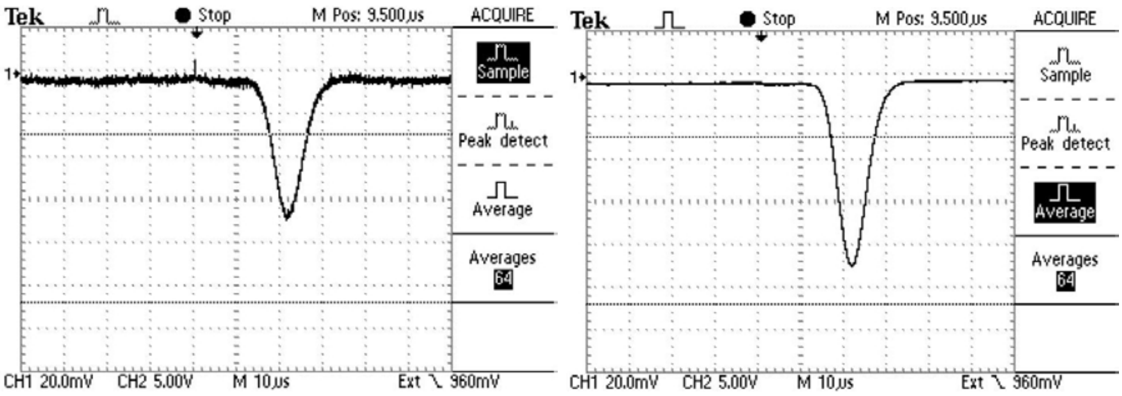


Figure 19: Left single acquisition; right average of 64 acquisitions

The signal-to-noise ratio may be greatly improved by averaging on many collected pulses, as shown in figure 19.

The digital oscilloscope screen is a matrix where the pixel corresponding to the signal traces have different color. The most common formats for downloading the screen content are graphic formats (*bitmapped*, as BMP, JPG…) or numeric (values comma separated as CVS or ASCII characters as TXT). In the second case the pulse is recorded as two columns matrix, where the first column contains the pixels abscissa (time) and the second column the pixels ordinate (voltage).

A software application with graphical analysis features (e.g. Origin or Kaleidagraph) allows an easy data handling, including base-line subtraction and Gaussian interpolation.

Figure 20 shows an example of data handling with Origin.

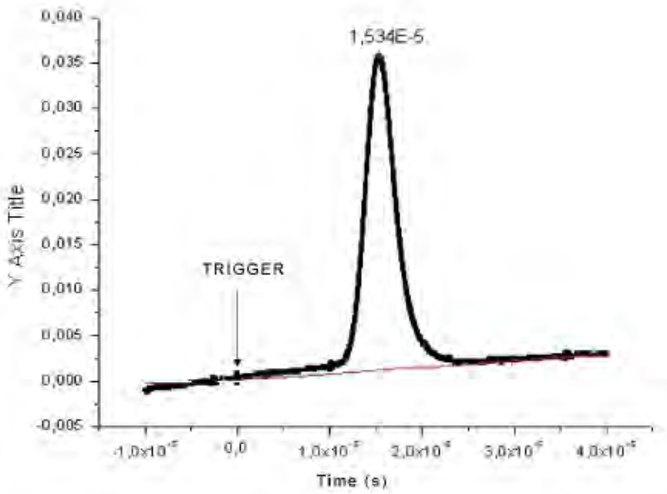


Figure 20: pulse recorded on PC memory with base-line interpolation

Appendix 4: Experimental values from literature

Drift mobility and diffusion constant at 300K :

	μ_e (cm^2/Vs)	μ_h (cm^2/Vs)	D_e (cm^2/s)	D_h (cm^2/s)
Ge	3900±100	1900±50	101	49
Si	1400±100	470±15	36	12

M.B. Prince, Phys. Rev. 92, 681 (1953) and Phys. Rev. 93, 1204 (1954); G.W. Ludwig, R.L. Watters, Phys. Rev. 101,1699 (1956). D is calculated from $D=\mu(kT/e)$.

	μ_e	μ_h	D_e	D_h
Ge	3900	1900	100	50
Si	1400	450	36	12

http://www.ioffe.rssi.ru/SVA/NSM/Semicond/Si/electric.html#Basic

Appendix 5: Arduino routine code

```
//LB 14/01/2016
#include <LiquidCrystal.h>
#include <SD.h>
#include <SPI.h>
#define CW true
#define CCW false
#define POSITION true
#define VOLTAGE false
#define V1 A0  // Laser voltage analog input
#define V2 A1  // Sweep voltage analog input
#define SXLS A2  // Left limit switch (active low)
#define DXLS A5  // Right limit switch (active low)
#define SX 2  // Left button (active low)
#define DX A4  // Right button (active low)
#define CAL A3  // Mode button (high = "Move fiber", low = "Distance calibration")
#define STEP 3  // Step signal to step motor driver
#define DIR 4  // Direction signal to step motor driver
const int backlash = 20;  // Backlash [number of steps]
const int nMean = 10; // Number of means
const unsigned long visTime = 1000;  // Visualization time [ms]
const unsigned long acqTime = 500;  // Acquisition time [ms]
boolean prevMonitor = POSITION;
int number[7];
unsigned long actual, lastVis, lastDaq, lastStep;
long pos;
float mm;
float v1, v2;
int i;
LiquidCrystal lcd(10, 9, 8, 7, 6, 5);
File myFile;
void setup()
{
 lcd.begin(16, 2);
 lcd.print("Starting...");
 pinMode(SXLS, INPUT);
 pinMode(DXLS, INPUT);
 pinMode(SX, INPUT);
 pinMode(DX, INPUT);
 pinMode(CAL, INPUT);
 pinMode(STEP, OUTPUT);
 pinMode(DIR, OUTPUT);
 digitalWrite(STEP, LOW);
 // Load last saved distance in number of steps
 lastVis = millis();
 if(SD.begin())
 {
  lcd.setCursor(0,0);
  lcd.print("   SD card OK   ");
  if(SD.exists("Position.txt"))
  {
   myFile = SD.open("Position.txt", FILE_READ);
   for(i=0; (number[i]=myFile.read())!=-1;i++)
   {
    Serial.println(number[i]-48,DEC);
   }
   number[i] = NULL;
   myFile.close();
   if((number[0]-48)==-3)
   {
    for(int n=1; n<i; n++)
    pos += (number[n]-48)*pow(10.0, i-(n+1));
    pos = pos*(-1);
   }
   else
   {
    for(int n=0; n<i; n++)
    pos += (number[n]-48)*pow(10.0, i-(n+1));
   }
   mm = pos / 800.0;  // Screw pitch = 1 mm _ Micostep 1/4
  }
```

```
    else
      mm = 0.0;
    delay(1000);
  }
  else
  {
    lcd.setCursor(0,0);
    lcd.print(" SD card ERROR! ");
    mm = 0.0;
    delay(5000);
  }
}

void loop()
{
  // MOVE SECTION
  if(!digitalRead(DXLS))
  {
    // Right limit switch engaged
    if(digitalRead(CAL))
    {
      // "Move fiber" mode
      if(!digitalRead(SX) || !digitalRead(DX))
      {
        lcd.setCursor(5,1);
        lcd.print(mm, 1);
        if(!digitalRead(SX) && digitalRead(SXLS))
        {
          // Move left
          lcd.clear();
          lcd.print(" Distance [mm]  ");
          moveMotor(CCW);
        }
        if(!digitalRead(DX) && digitalRead(DXLS))
          // Move right
          moveMotor(CW);
        lastVis = millis();
      }
    }
    else
    {
      // "Distance calibration" mode
      if(!digitalRead(SX) || !digitalRead(DX))
      {
        lcd.clear();
        lcd.print(" Calibrate [mm]  ");
        lcd.setCursor(5,1);
        lcd.print(mm, 1);
        calibrateMotor();
        lastVis = millis();
      }
    }
  }
  else
  {
    // Right limit switch free
    if(!digitalRead(SX) || !digitalRead(DX))
    {
      if(!digitalRead(SX) && digitalRead(SXLS))
      {
        // Move left
        lcd.clear();
        lcd.print(" Distance [mm]  ");
        lcd.setCursor(5,1);
        lcd.print(mm, 1);
        moveMotor(CCW);
      }
      if(!digitalRead(DX) && digitalRead(DXLS))
      {
        // Move right
        lcd.clear();
        lcd.print(" Distance [mm]  ");
        lcd.setCursor(5,1);
```

```
      lcd.print(mm, 1);
      moveMotor(CW);
    }
    lastVis = millis();
  }
 }
 // DISPLAY SECTION
 if(millis() >= (lastVis + visTime) && prevMonitor)
 {
   // Display Laser and Sweep voltage in V
   misura();
   lcd.clear();
   lcd.print("VL=");
   lcd.print(v1+.05, 1);
   lcd.setCursor(9,0);
   lcd.print("VS=");
   lcd.print(v2+.05, 1);
   lcd.setCursor(0,1);
   lcd.print("  d= ");
   lcd.print(mm, 1);
   lcd.print(" [mm]  ");
   prevMonitor = VOLTAGE;
   lastVis = millis();
 }
 else if((millis() >= (lastDaq + acqTime)) && !prevMonitor)
 {
  // Acquire Laser and Sweep voltage every acqTime ms
  misura();
  lcd.setCursor(3,0);
  lcd.print(v1+.05, 1);
  lcd.print(" ");
  lcd.setCursor(12,0);
  lcd.print(v2+.05, 1);
  lcd.print(" ");
 }
}

// Motor move function
void moveMotor(boolean dir)
{
 short i = 0;
 digitalWrite(DIR, dir);
 if(dir == CW)
 {
  // Move right
  while(!digitalRead(DX) && digitalRead(DXLS))
  {
    digitalWrite(STEP, HIGH);
    lastStep = micros();
    mm -= 0.00125;
    digitalWrite(STEP, LOW);
    if(i==0)
      lcd.setCursor(5,1);
    else if(i==1)
      lcd.print(mm, 1);
    else if(i==2)
    {
      lcd.print("  ");
      i=-1;
    }
    i++;
    while(micros() < (lastStep + 2000));  // Step frequency = 500Hz
  }
  // Backlash recovery
  for(i = 0; i < (backlash * 2); i++)
  {
    if(i == backlash)
    {
      digitalWrite(DIR, CCW);
      delay(10);
    }
    digitalWrite(STEP, HIGH);
    delayMicroseconds(200);
```

```
      digitalWrite(STEP, LOW);
      delayMicroseconds(1800);
    }
  }
  else
  {
    // Move left
    while(!digitalRead(SX) && digitalRead(SXLS))
    {
      digitalWrite(STEP, HIGH);
      lastStep = micros();
      mm += 0.00125;
      digitalWrite(STEP, LOW);
      if(i==0)
        lcd.setCursor(5,1);
      else if(i==1)
        lcd.print(mm, 1);
      else if(i==2)
      {
        lcd.print("  ");
        i=-1;
      }
      i++;
      while(micros() < (lastStep + 2000));  // Step frequency = 500Hz
    }
  }
  if(!digitalRead(DXLS) || !digitalRead(SXLS))
  {
    lcd.setCursor(0,0);
    lcd.print(" Limit switch!! ");
  }
  prevMonitor = POSITION;
  // Save actual distance in number of steps
  pos = mm * 800.0;
  if(SD.exists("Position.txt"))
    SD.remove("Position.txt");
  myFile = SD.open("Position.txt", FILE_WRITE);
  myFile.print(pos, DEC);
  myFile.close();
}

// Motor calibration function
void calibrateMotor()
{
  while(!digitalRead(SX))
  {
    mm -= .1;
    lcd.setCursor(5,1);
    lcd.print(mm, 1);
    lcd.print("  ");
    delay(250);
  }
  while(!digitalRead(DX))
  {
    mm += .1;
    lcd.setCursor(5,1);
    lcd.print(mm, 1);
    lcd.print("  ");
    delay(250);
  }
  prevMonitor = POSITION;
  // Save actual distance in number of steps
  pos = mm * 800.0;
  if(SD.exists("Position.txt"))
    SD.remove("Position.txt");
  myFile = SD.open("Position.txt", FILE_WRITE);
  myFile.print(pos, DEC);
  myFile.close();
}

// Measure function
void misura()
{
```

```
  v1 = v2 = 0.0;
  for(int i = 0; i < nMean; i++)
  {
    v1 = v1 + analogRead(V1);
    v2 = v2 + analogRead(V2);
  }
  v1 = (30 * v1 / (1024 * nMean));  // Laser voltage in V
  v2 = (50 * v2 / (1024 * nMean));  // Sweep voltage in V
  lastDaq = millis();
}
```

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