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A simple apparatus for the measurement of minority carrier lifetime in semiconductors

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Abstract A simple technique that allows a direct reading of the minority carrier lifetime in semiconductor crystals is described. The experiment is suitable for an undergraduate laboratory course, and it requires only a double trace oscilloscope and low cost electronic components.

Riassunto Si descrive un metodo per ottenere misure rapide e dirette di vita media di portatori minoritari in cristalli semiconduttori. L'esperimento è concepito per un laboratorio didattico per laurea in fisica, e richiede solo l'uso di un oscilloscopio a doppia traccia e di componenti elettronici a basso costo.

1. Introduction

The measurement of excess minority carrier lifetime and the understanding of the associated recombination mechanism is an important step in an introductory solid state laboratory course.

Many techniques for measuring minority carrier lifetime have been reported and a general review on this subject, with an extended bibliography, is given by Runyan (1975).

The wide choice among the various techniques, however, is severely restricted by the need for practicality and simplicity when an educational experiment is considered. For this purpose the only reasonable choice is between the 'pulse decay' method (PD) and the 'photoconductive decay' method (PCD).

The PD technique (Many 1954) requires a weakly injecting contact at one end of the semiconductor sample. It is not simple to make contacts with proper injecting characteristics, in fact the successful procedure depends on the semiconducting material and on the dopant (Walsh 1962). As a consequence the students' efforts would probably be devoted more to practice in making contacts than to investigating the physical phenomena involved in the experiment.

The PCD method avoids this difficulty by optically injecting the excess minority carriers. This technique has been proposed in several versions (Stevenson and Keyes 1955, Armstrong 1957, Watters and Ludwig 1956, Engler and Kevane 1957, Richardson and Meese 1978, Chow 1984), where the light pulses are produced by fast mechanical choppers or flash lamps. Such light sources, however, are usually expensive and delicate instruments that are rarely available in standard teaching laboratories.

To overcome these difficulties we propose a simple PCD technique where a commercial grade infrared light emitting diode (LED) is used as light source.

2. Description of the method

In our experiment a bar-shaped semiconductor crystal has two low-resistance contacts at the ends, and is biased by a constant current generator. The light pulse penetrates into the crystal generating an excess of electron–hole pairs. The change ΔV_p in the voltage drop across the sample, due to the conductivity change, is displayed on an oscilloscope screen.

Let us assume the following ideal conditions: (i) zero surface recombination velocity; (ii) a sweep-out time of the excess carrier much longer than the recombination lifetime; (iii) weak photoinjection; and (iv) absence of temporary traps.

With these assumptions, and with a light pulse of constant intensity beginning at time $t = 0$ and end-

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ing at $t = t_0$, we expect for ΔV_p the exponential behaviour (Smith 1978)

$$\begin{aligned} \Delta V_p(t) &= \Delta V_{ps}[1-\exp(-t/\tau)] \quad \text{for } 0 \leqslant t \leqslant t_0 \\ \Delta V_p(t) &= \Delta V_{po}\exp[-(t-t_0)/\tau] \quad \text{for } t \geqslant t_0, \end{aligned} \tag{1}$$

where ΔV_{ps} is the voltage change that should be observed in steady state conditions ($t_0 \to \infty$), τ is the bulk minority carrier lifetime and $\Delta V_{po} = \Delta V_{ps}[1-\exp(-t_0/\tau)]$.

In order to check relation (1) and to measure τ it is convenient to compare the experimental photoconductive signal with a reference signal $V_R(t)$ obtained by passing the LED driving square pulse through a RC low-pass filter. The time dependence of V_R is the same as in (1) with $\tau = RC$, so that in ideal conditions a perfect matching of the two signals should be achieved on a double trace CRT screen by properly adjusting the time constant RC and the amplitude of the reference signal V_R.

In a real experiment, however, the exponential signal described by (1) can be seriously distorted by various effects, so that some care must be taken when performing the lifetime measurement.

(i) The surface recombination effect may become important for samples with poorly polished surfaces and/or with large surface-to-volume ratio, or when the excess carriers are generated very close to the sample surface owing to a high absorption coefficient at the chosen wavelength. In these cases the observed time constant can be much shorter than the bulk recombination lifetime (Bray and Many 1959). Therefore large crystal dimensions and clean surfaces are to be preferred, and infrared light near the fundamental absorption edge must be chosen.

(ii) If the mean time τ_d within which the injected carriers are swept out of the sample is comparable with the lifetime τ, the exponential signal tends to saturate at $t = \tau_d$. This effect, however, can be avoided using a sufficiently small bias voltage V_{po}. For example, with the light spot placed midway between the end contacts, one must satisfy the inequality: $V_{po} < l^2/(2\mu\tau_d)$, where l is the sample length and μ is the minority carrier mobility.

(iii) The condition of weak photoinjection may be written $\Delta n \ll n_0 + p_0$, where $\Delta n = \Delta p$ is the excess carrier density and n_0 and p_0 are the equilibrium densities of electrons and holes respectively. If this condition is released, i.e. if the excess carrier generation rate is too large, then ΔV_p ceases to be simply proportional to Δn (Watters and Ludwig 1956). The photoconductive signal in this case is no longer a simple exponential, and its initial decay rate is smaller than the lifetime τ. A useful 'rule of thumb' to exclude overinjection is to keep the relative conductivity change $\Delta\sigma/\sigma = -\Delta V_p/V_p$ within a few per cent.

(iv) When the recombination is affected by a trapping mechanism, the theoretical prediction for the photoconductive signal becomes quite complex (Fan 1953) and the rising and falling part of the signal are generally expected to have different time constants. In the particular case where only 'safe' traps are important, the signal should exhibit two decay time constants after the illumination has been cut off (Smith 1978): if τ_1 is the mean time that a carrier spends in a safe trap, with $\tau_1 \gg \tau$, then one should observe a fast exponential drop with time constant τ, followed by a long tail with time constant τ_1.

Experimental measurements have shown that at room temperature the trapping is important in Si crystals, but not in Ge crystals (Haynes and Hornbeck 1953).

Some examples of the effects described in (i)–(iv) will be reported in §4.

3. Experimental apparatus

The complete experimental set-up is shown in figure 1. One general purpose operational amplifier (OA1) with floating power supply (two 9 V dry cells) provides the bias voltage V_{po} to the semiconductor crystal.

OA1 works as a constant current generator, the current I_s being adjusted by the potentiometer P1 at negative or positive values. The value of the selected current is obtained, as $I_s = V_s/R_s$, from the voltage drop across the feedback resistor R_s. This voltage can be read on oscilloscope channel 2 when the commutator SW is in position 1.

With SW in position 2 the oscilloscope in the DC coupling mode displays the total voltage $V_p(t) = V_{po} + \Delta V_p(t)$ across the sample. Once V_{po} has been measured, the oscilloscope is set into the AC mode, and $\Delta V_p(t)$ can be properly amplified.

In order to reduce the pick-up noise, associated with this small signal, the sample is placed inside a grounded metallic box together with the constant current generator. The light pulse is fed onto the crystal through a hole in the box wall.

The second IC(OA2), connected in the astable multivibrator configuration, produces a square pulse V_M whose duration t_0 can be adjusted by means of the potentiometer P2 ($100\ \mu s < t_0 < 1$ ms), the duty cycle always being less than 10^{-1}.

Starting from this main pulse V_M, we obtain both the LED driving pulse (by means of the current booster stage OA4) and the reference signal V_R (by means of the buffer stage OA3 and the low-pass filter).

The filter time constant RC is selected by setting the R value on a decade resistance box (P3), while C is a calibrated capacity ($C = 100$ nF). V_R is then fed to the oscilloscope and its amplitude is adjusted by using the variable gain of the channel 1 amplifier.

The LED forward current I_L can be adjusted by the potentiometer P4 ($10\ mA < I_L < 1$ A), and it is

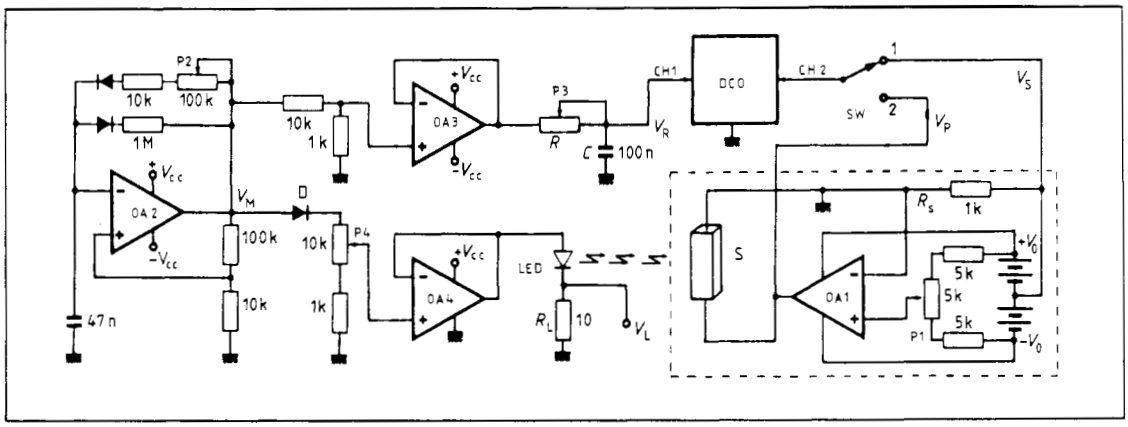

Figure 1 The electronic circuit for signal generation and detection. DCO is a double channel oscilloscope, S is the semiconductor sample, OA1, OA2 and OA3 are fast operational amplifiers (Texas TL 081 or National LF 356), while OA4 is a high power, high slew rate operational amplifier (Siemens TCA 365 or SGS-ATES L165).

measured as a voltage drop V_L across the 10 Ω resistor R_L. The diode D clamps the negative swing of V_M at the OA4 input.

OA2 and OA3 are power supplied by a twin-voltage stabilised source ($V_{cc} = \pm 15$ V), while OA4 is connected between $+V_{cc}$ and the common ground. To prevent instabilities of the circuit, both the positive and the negative voltage supplies are connected to large stabilising capacitors (100 μF).

As the infrared LED we used the low cost TIL 32, whose wavelength at peak emission is $\lambda_p = 940$ nm, with a bandwidth $\Delta\lambda = 7$ nm. With this device the light beam does not need a collimator, because 80% of the irradiated power is focused within an angle of 10°. Close replacements of Texas TIL 32 are TWR OP 160 and General Electric SSL3.

The rise and decay times of the V_L pulse are determined principally by the slew rate of OA4 (4 V μs^{-1} for TCA 365). The LED intrinsic rise time is smaller than 1 μs, and our typical light-on and light-off times are less than 2 μs.

4. Sample preparation and experimental results

Measurements of photoconductive signals have been performed with different germanium and silicon samples of p and n type.

The Ge samples were bars of square cross section (0.3 × 0.3 cm^2) 3 cm long, and the Si samples were 5 cm long with rectangular cross sections (1 × 0.3 cm^2). They were first ground with #800 wet carborundum paper, then lapped with alumina powder until a mirror-like surface was obtained, and finally washed in acetone.

The contact ends were etched with CP4 (60% HNO_3, 30% CH_3COOH, 10% HF), and, in the case of germanium, directly tinned with a common soldering iron. This simple technique usually gives low resistance contacts both in n-type and p-type Ge.

A different procedure must be used on silicon as the solder alloy does not wet the crystal surface. We found, however, that after a thick electrolytical nickel plating one can obtain (with the normal PbSn alloy) soldered contacts which have low resistance both in n-type and p-type Si. Figure 2 shows some typical photoconductive signals obtained under the experimental conditions described in table 1. The time constant RC of the reference signal V_R has been chosen each time to best fit the photoconductive signal ΔV_p. The matching between V_R and ΔV_p is quite good only in the figures 2(a) and 2(b), namely those obtained under the nearly ideal

Figure 2 The photoconductive signal ΔV_p and the reference signal V_R as displayed on the oscilloscope screen. The x axis (sweep time) is 200 μs div^{-1}. The y axis is 5 mV div^{-1} for (a), (b), (d), (e) and (f) and 50 mV div^{-1} for (c). A better resolution can be achieved if a digital storage oscilloscope and a chart recorder are available.

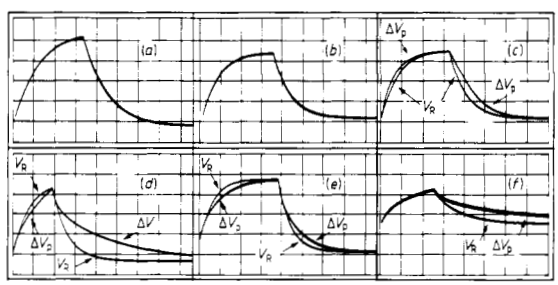

Table 1 Experimental conditions for the measurements shown in figure 2. The lifetime is typically measured within ±5%.

Figure number	2(*a*)	2(*b*)	2(*c*)	2(*d*)	2(*e*)	2(*f*)
Sample	Ge p	Ge n	Ge n	Si p	Si p	Si n
Resistivity (Ω cm)	17	27	27	52	50	7
Dopant concentration (cm^{-3})	2×10^{14}	5×10^{13}	5×10^{13}	3×10^{14}	3×10^{14}	10^{15}
Bias voltage V_{po} (V)	2.4	1.8	1.8	2.8	2.8	0.8
LED current I_L (mA)	10	10	140	100	230	900
Time constant RC (μs)	220	180	180	130	110	240

condition described in §2 ((ii), (iii) and (iv)): the bias voltage V_{po} is small enough to provide a sweeping time τ_d longer than the lifetime τ, the light injection is weak ($\Delta\sigma/\sigma \simeq 10^{-2}$) and the germanium samples exhibit negligible trap effects. As far as point (i) of §2 is concerned, we notice that the measured τ values are smaller than the true bulk lifetimes of the original crystal, because the surface recombination velocity is not negligible owing to the small lateral dimensions of our samples.

A simple method to show the students the effect of surface recombination on the observed lifetime is to repeat the measurement after roughening the sample surfaces one by one. The measured τ decreases at each step, and it can be reduced to half the original value when three out of four of the lateral facets have been roughened. The illuminated surface must be kept polished, otherwise the excess carriers, which are produced mostly close to this surface, suffer an enhanced recombination. When the illuminated surface is also roughened, the observed lifetime is likely to decrease by one order of magnitude.

Figure 2(*c*) was obtained under the same conditions as figure 2(*b*), but with a larger light pulse amplitude ($\Delta\sigma/\sigma = 8.6\times10^{-2}$). ΔV_p increases by an order of magnitude, but it is clearly not exponential, due to the overinjection effect.

Figures 2(*d*), 2(*e*) and 2(*f*) have been obtained using silicon samples. The last one has been obtained with a crystal so highly doped that the photoconductive signal is hardly measurable even with maximum light intensity. In all these three figures the departure from the exponential behaviour is apparent, and the long tail that follows the initial fast drop shows the effect of the 'safe traps' previously mentioned.

5. Conclusions

Compared with other PCD equipments described in the literature, this offers some remarkable advantages that make it a valuable tool in the solid state physics teaching laboratory.

The time constant of the leading exponential in the PCD signal is measured by a fast and simple procedure, which avoids oscilloscope trace recording and exponential data fitting (Chow 1984).

The electronic circuitry is simple and does not require particular skill to be assembled and properly adjusted by the student personally.

The pulsed light source is much more compact and easy to handle than mechanical choppers, it is free from the RF noise typical of flash lamps, and—last but not least—it is quite cheap.

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