Short Notes

The Haynes-Shockley Experiment with Silicon Planar Structures

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Abstract—**A Haynes-Shockley experiment is described which is performed on silicon planar structures instead of on the usual germanium filaments. The drift field is realized by planar ohmic contacts, which are properly positioned to ensure a homogeneous field in the measuring area. The structures have been thoroughly tested, and the measurements yield the expected minority carrier drift mobility and lifetime. The silicon structures relieve the student of the laborious preparation of the normally used germanium filaments.[1]**

I. Introduction

The celebrated Haynes-Shockley experiment allows the simultaneous measurement of the drift mobility μ, the diffusion coefficient D and the lifetime τ of minority carriers in semiconductors [1]. In the experiment minority carriers are injected into a germanium filament with a point contact emitter. They are swept down the filament by a variable electric field and collected by another point contact along the filament. From the signal at the collector, the values μ, D and τ can be derived.

Because of its elegance, the Haynes-Shockley experiment is a favorite assignment in an undergraduate laboratory course in semiconductor device physics [2]. This is not always to the enjoyment of the students, since the preparation of the germanium surfaces and the forming of the point contacts is usually rather troublesome and, moreover, outdated with respect to present technology. In this paper a Haynes-Shockley experiment is described which is performed on silicon structures which are obtained by the standard planar technology with which bipolar integrated circuits are fabricated.

Since the minority carrier lifetime τ at the silicon surface is much lower than the lifetime in bulk germanium, the dimensions of the structure and the pulse program differ considerably from those used in the germanium experiment. In the next sections the relevant theory, the layout of the structure, the drive electronics and some measurement results are presented.

II. Theory

In the modified Haynes-Shockley experiment, minority carriers are generated at E (Fig. 1) by applying a short current pulse to an emitter contact at E [3, 4] or by a light or electron beam pulse [5].

When we consider a uniform one-dimensional system in which P_0 holes are injected at E (Fig. 1) at a point $x = 0$ at time $t = 0$, the continuity equation is as follows:

$$D_p \frac{\delta^2 p'}{\delta x^2} - \mu_p E_0 \frac{\delta p'}{\delta x} - \frac{p'}{\tau_p} = \frac{\delta p'}{\delta t} \tag{1}$$

in which D_p is the diffusion coefficient for holes, p' is the excess hole density, μ_p is the hole mobility, E_0 is the applied electric field, and τ_p is the hole lifetime [2, 6].

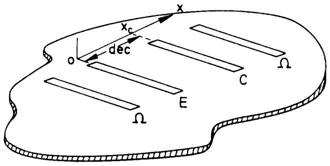

Fig. 1. Basic features of the Haynes-Shockley method.

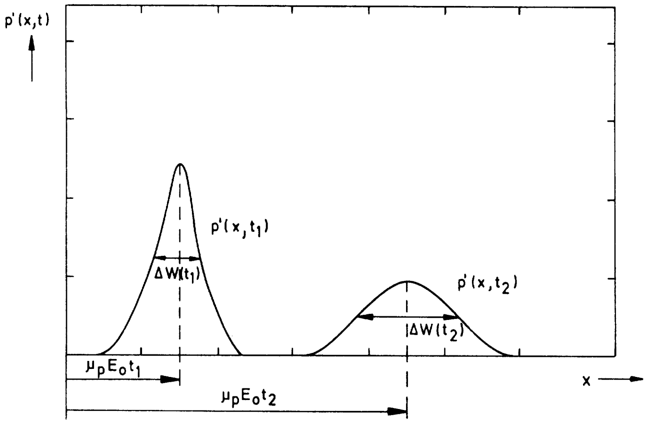

Fig. 2. Excess hole density as a function of x for $t_2 > t_1 > 0$ at time $t = 0$, holes are injected at $x = 0$.

The solution for the excess hole density $p'(x, t)$ as a function of place and time in an n-type extrinsic semiconductor is (Fig. 2)

$$p'(x,t) = \frac{P_0}{2\sqrt{\pi D_p t}} \exp\left(\frac{-(x - \mu_p E_0 t)^2}{4 D_p t}\right) \exp\left(\frac{-t}{\tau_p}\right). \tag{2}$$

From an experimental determination of $p'(x, t)$, the mobility μ_p, the diffusion coefficient D_p and the hole lifetime τ_p can be determined.

a) Determination of μ_p

In a first approximation the maximum of the excess hole density moves along the x-axis with a velocity v equal to $\mu_p E_0$. When the time t_0 is required for the maximum to traverse the distance d_{ec} (Fig. 1) between emitter and collector, the mobility μ_p can be calculated from

$$v t_0 = d_{ec} \tag{3}$$

or

$$\mu_p = \frac{d_{ec}}{t_0 E_0}. \tag{4}$$

b) Determination of D_p

The diffusion coefficient D_p can be obtained from the half-width $\Delta W(t)$ of the curve at time t. We find that

$$\frac{1}{4} \frac{P_0}{\sqrt{\pi D_p t}} = \frac{P_0}{2\sqrt{\pi D_p t}} \exp\left(\frac{-\Delta W^2(t)}{8 D_p t}\right) \tag{5}$$

and

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[1] Interested colleagues may obtain a limited number of devices free by writing to either of the authors.

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$$\Delta W(t) = \sqrt{11 D_p t}, \tag{6}$$

so that

$$D_p = \frac{\Delta W^2(t)}{11t}. \tag{7}$$

By means of an oscilloscope, the collector signal can be observed. However, this signal represents the excess hole density as a function of time t and not as a function of distance x. To obtain $\Delta W(t)$, the halfwidth of the collector signal $\Delta t(x_c)$ must be multiplied with the local velocity $v = \mu_p E_0$ with which the cloud of holes passes the collector:

$$\Delta W(t) = \mu_p E_0 \Delta t(x_c). \tag{8}$$

And combining Eq. (6) and (8) we obtain

$$D_p = \frac{\mu_p^2 E_0^2 \Delta t^2(x_c)}{11t}. \tag{9}$$

c) Determination of the Lifetime τ_p

From the amplitude or, better, from the area of the collector signal, the hole lifetime τ_p can be obtained. To calculate the total number of excess holes p' as a function of time, Eq. (2) can be integrated over x between $-\infty$ and $+\infty$:

$$p'(t) = \int_{-\infty}^{+\infty} p'(x,t)\, dt = P_0 \exp\left(\frac{-t}{\tau_p}\right). \tag{10}$$

The total number of excess holes falls off exponentially with time. The lifetime τ_p can be calculated from a comparison of the area of the emitter and collector signal. As will be described in the section on measurements, this comparison is rather difficult, since the collector efficiency is not known.

III. EXPERIMENTAL H-S STRUCTURE AND ELECTRONIC CIRCUIT

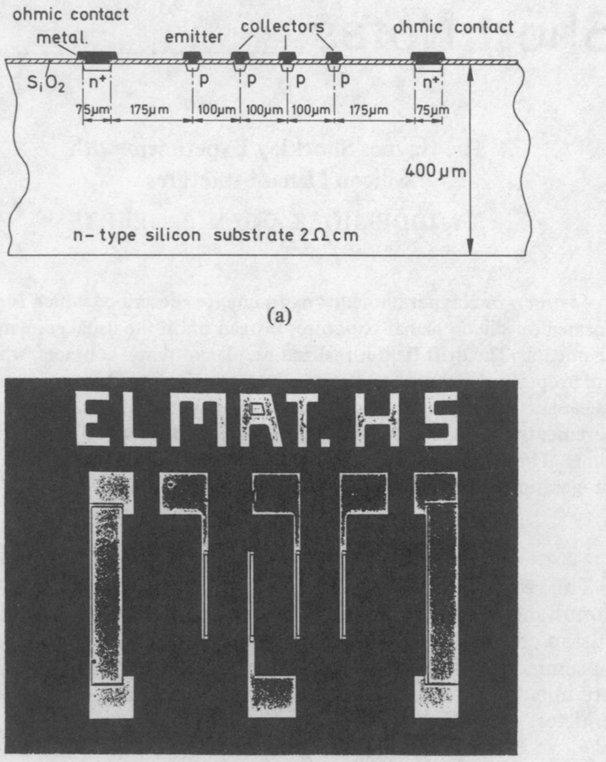
As shown in Fig. 3 the Haynes-Shockley structure consists of two elongated n^+-type ohmic contacts between which one elongated p-type emitter and three elongated p-type collectors are placed in a 2 Ω · cm n-type substrate by means of the standard base diffusion process.

The contacts are made of aluminum, and the whole chip is mounted electrically isolated in a TO-5 package with aluminum wires connecting the bonding pads with the posts. Even though the oxidation furnace was treated with HCl, the surface recombination was severe, leading to short lifetimes.

For this reason the distance between the emitter and collectors are chosen to be only 100 μm. This small distance, in turn, requires narrow emitter and collector contacts. The oxide windows for the diffusion areas are chosen to be 9 μm which leads, because of lateral diffusion, to electrodes with an effective width of about 12 μm. The distance between the ohmic contacts is made rather large, to ensure that the electric field, caused by a voltage on these contacts, will be homogeneous in the zone of measurement. In the traditional germanium filaments with ohmic end contacts, the homogeneity of the field is less of a problem.

Figure 4 shows the potential drop along the used planar structure, as measured by compensating the internal voltage. In the zone of measurement (E to C_3), the potential changes linearly with the distance as required, although the electric field is considerably smaller than the value expected from the division of the applied voltage by the total distance between the ohmic contacts.

To facilitate the measurements two additional collectors C_2 and C_3 are used; the reason for this will be made clear in the section on measurements.



(a)

(b)

Fig. 3. (a) Cross section and (b) photo of the planar silicon structure for the Haynes-Shockley experiment.

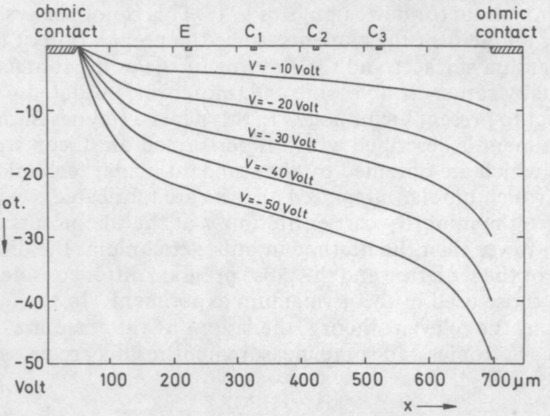


Fig. 4. Potential distribution along the cross section of the H-S structure for different voltages between the ohmic contacts.

The block diagram of the electronic circuitry used for the H-S experiment is shown in Fig. 5.

The sweep electric field is obtained by means of a power supply and a pulse generator. The base of the intermediate transistor is positively pulsed; a pulse width of 5 μs and a pulse repetition rate of 100 Hz are used.

The sweep field is pulsed in order to avoid heating effects, when high pulse amplitudes are used. The collectors are connected via resistors to the same sweep voltage. Since the collectors are in between the two ohmic contacts, the collectors are always biased in the reverse direction and will only collect minority carriers (in our case these are holes). The emitter is biased in such a way that no forward current is present. The pulse from the pulse generator causes the emitter to inject a determined number of holes. The pulse width can be adjusted between 10 ns and 100 ns and the pulse amplitude, between zero and three volts. The triggering of this pulse generator and

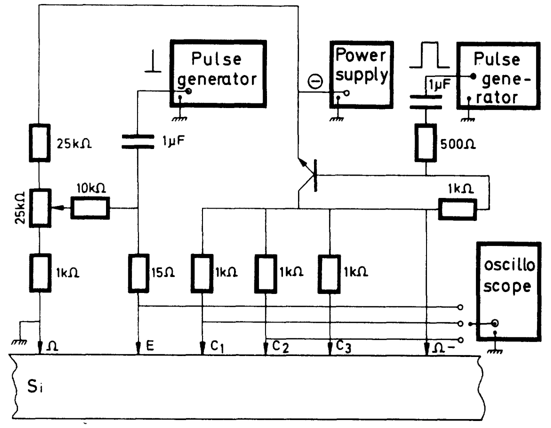


Fig. 5. Block diagram of the electronic circuitry used for the Haynes-Shockley experiment.

the sweep field generator is synchronized, and a proper delay between the rising edges of the pulses is adjusted. If the collectors are biased by a separate power supply, independent of the sweep voltage, it appears that the collector efficiency depends on the bias voltage. Moreover, it appears that the arrival rate of holes at collector C_3 depends on the number of holes collected at C_1 and C_2. Also the collection of holes at C_1 has an influence on the arrival rate at C_2, as expected. As we will see these effects can be employed to obtain the hole lifetime τ_p.

IV. Experimental Results

Figure 6 shows a sketch of a typical oscilloscope trace obtained by the described experimental arrangement. The first pulse in the collector signal is due to the injection pulse at the emitter. From the transit time t_d between this pulse and the maximum of the second broad pulse, the mobility μ_p can be deduced. From the width of the pulse, the diffusion coefficient D_p can be obtained, whereas the area of the pulse is a measure of the hole lifetime τ_p.

a) Measurement of the Mobility μ_p

In order to obtain a reasonably measurable collector signal, a rather large injection of holes at the emitter contact is required. This leads to a significant increase of the current carrier density around the emitter contact. This in turn has a large influence on the field distribution in the substrate. The drift field in the neighborhood of the emitter is smaller than expected from Fig. 4. Therefore, the initial velocity of the cloud of holes in the direction of the collector contacts is very small. The mobility calculated from the time interval between the emitter pulse and the maximum of the collector signal will be much smaller than the real mobility.

The true mobility can be obtained by different methods. In the usual way the transit time is measured as a function of the number of the injected holes, and this curve is extrapolated to zero injection. It is also possible to measure the mobility at a place on the substrate which is far removed from the emitter and where conductivity modulation is nonexistent.

For this purpose the original simple Haynes-Shockley structure is extended in our experiments with two additional collector contacts C_2 and C_3 (Fig. 3).

The transit times t_2 and t_3 between emitter and collectors 2 and 3, respectively, are measured. From these transit times the time interval t_{23} between C_2 and C_3 can be deduced as a function of the electric field for constant injection at the emitter. In Fig. 7 the velocities obtained from the transit time t_{23} are shown. The curve for v_{23} is a straight line from which a hole mobility $\mu_p = 458$ cm^2/V · s can be calculated easily.

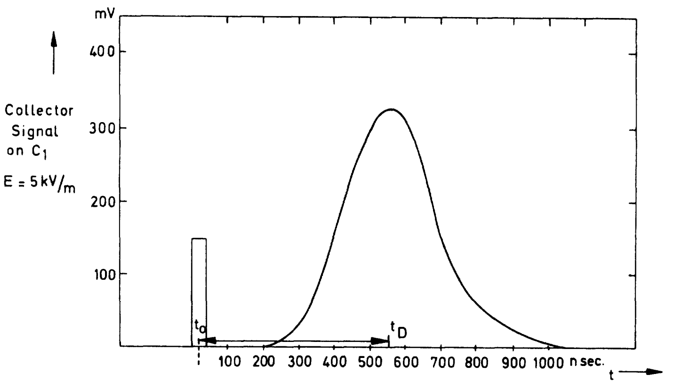


Fig. 6. Sketch of a typical oscilloscope trace of a collector signal at C_3.

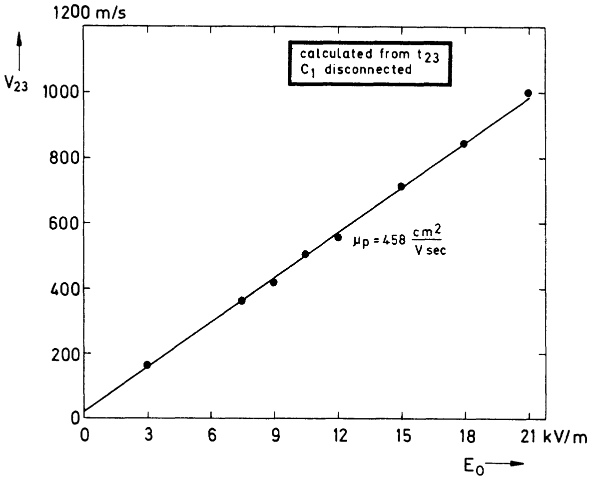


Fig. 7. Velocity of the hole packet between C_2 and C_3 as a function of the electric field E_0. Collector C_1 is not connected.

This value fits reasonably well with the values reported in the literature [4]. The straight line v_{23} does not pass through the origin, but intersects at about $v_{23} = 15$ m/s. This is due to the fact that even without a sweeping field a pulse is observed at the collectors. This signal is caused by the diffusion process described by McKelvey [6]. The influence of this diffusion process decreases, the more the drift field is increased. When we correct for the diffusion process by using the largest value of v_{23}, we ascertain that μ_p is equal to 466 cm^2/V · s.

b) Measurement of the Diffusion Coefficient D_p

The Haynes-Shockley experiment is seldom used to measure the diffusion coefficient [7]. Because of the injection pulse width, the width of the emitter and collector contacts, the conductivity modulation at the emitter, the small distance between emitter and collector contacts, the small lifetime τ_p in silicon, the recombination and trapping of holes at the surface and because of the fact that diffusion occurs in three dimensions, the measurement of the diffusion coefficient D_p by means of the Haynes-Shockley experiment cannot be very reliable.

Two D_p measurement methods can be distinguished. In the first method, from the collector signals at C_1, C_2 or C_3, which show the hole density as a function of time, the spacial distribution can be deduced. This can be achieved by multiplying the collector signal at, for instance, C_3 with the velocity of the hole packet between C_2 and C_3, which is obtained by measuring the time interval t_{23} between the maxima of the signals at C_2 and C_3. Applying an electric field of $E_0 = 18$ kV/m, the halfwidth of the collector signal is 270 ns and the maximum is at 615 ns. From Fig. 7 we find that the velocity at C_3 is equal to 840 m/s. The halfwidth of the spacial distribution is then 226 μm. Using eq. (7) we find that $D_p = 75.5\ \mathrm{cm}^2/\mathrm{s}$. This value is much larger than the values reported in the literature [8]. Since the structure contains three collector contacts also, another, more direct way of measuring the halfwidth of the hole pocket is possible. When the signal at C_2 shows a maximum, we can assume that also the maximum of the spacial distribution is at C_2. Observation of the signals at C_1 and C_3 at this particular time will tell us then the hole densities at the collector contacts C_1 and C_3. It is a difficulty that the collector efficiencies of C_1, C_2 and C_3 are not known and can be different. Further at collectors C_1 and C_2 an appreciable amount of holes is removed, so that the collector signals cannot be directly compared. To circumvent the above problems the collector signal at C_3 is measured with disconnected C_1 and C_2 contacts and the C_2 signal is measured with a disconnected C_1 contact. With a separate power supply, the respective collector contacts are biased with the same voltage with respect to the part of the substrate which is right beneath the contact, so that the collector efficiencies are equal.

The collector signals at C_1, C_2 and C_3 obtained in this way are shown in Fig. 8. The time interval between injection and maximum collection at C_2 is 500 ns. From these signals a rough sketch (only three points are known) of the spacial distribution can be made (Fig. 9). We assume that the maximum of the distribution is at C_2. From the sketch we obtain an estimate of the halfwidth which reveals that ΔW (500 ns) is equal to 200 μ. Substituting this value and $t = 500$ ns in Eq. (7), we obtain a diffusion coefficient $D_p = 72.7\ \mathrm{cm}^2/\mathrm{s}$. This value is also much too large, and we must assume that the width of the hole packet is determined by other effects than by diffusion alone.

c) Measurement of the Hole Lifetime τ_p

The total number of excess holes $P'(t)$ decreases exponentially with time. A comparison of the number of injected holes at the emitter with the number of collected holes at C_1, C_2 and C_3 for different electric sweeping fields E_0 should enable the determination of τ_p [9]. A complication arises due to the fact that the collector efficiencies at C_1, C_2 and C_3 are not accurately known. To determine τ_p the areas of the collector pulses at C_2 and C_3 are measured as a function of the voltage on C_2.

When the number of excess holes arriving at C_2 is equal to P_2' and when the collector efficiency of C_2 is α_2; $P_2'\alpha_2$ holes will be collected and $P_2'(1 - \alpha_2)$ will pass on to C_3. Because of recombination at collector C_3, the number of holes arriving is $P_2'(1 - \alpha_2) \exp - t_{23}/\tau_p$, in which t_{23} is the time interval between the maxima of the signals at C_2 and C_3. Let α_3 be the collector efficiency at C_3, then the signal there is $P_2' \cdot \alpha_3(1 - \alpha_2) \exp - t_{23}/\tau_p$. This is illustrated in Fig. 10. If the collector voltage $V(C_2)$ at C_2 is changed, the collector signals at C_2 and C_3 also change. In Fig. 11 the signals are plotted as a function of the collector voltage $V(C_2)$. In order to calculate collector efficiencies α_2 and α_3 and the hole lifetime τ_p, we will compare the collector signal areas expressed in coulombs ($Q_2 = qP_2'$ and $Q_3 = qP_3'$) for a collector bias voltage $V(C_2)$ of 11 volts and 31 volts and an electric field $E_0 = 18$ kV/m. For the ratio of the C_3 signals we find

$$Q_3(31V)/Q_3(11V) = P_2' \cdot \alpha_3(1 - \alpha_2(31V)) \cdot \exp(-t_{23}/\tau_p)/P_2' \cdot \alpha_2(1 - \alpha_2(11V)) \cdot \exp(-t_{23}/\tau_p) = 0.91$$

or

$$(1 - \alpha_2(31V))/(1 - \alpha_2(11V)) = 0.91.$$

For the ratio of the C_2 signals we find

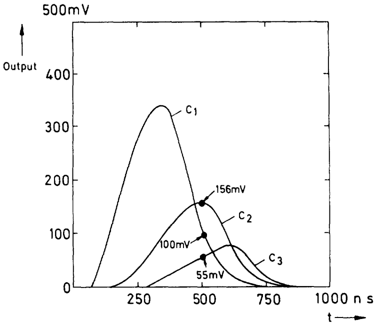


Fig. 8. Collector signals at C_1, C_2 and C_3 for an electric field of E_0 = 18 kV/m. The C_3 signal is measured with disconnected C_1 and C_2, the C_2 signal is measured with disconnected C_1.

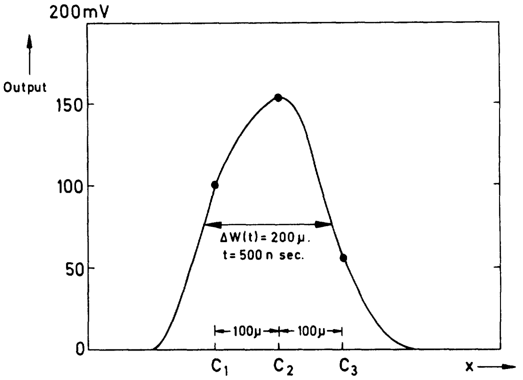


Fig. 9. Rough estimate of the spacial distribution of the hole packet under C_2 as constructed from the curves of Fig. 7.

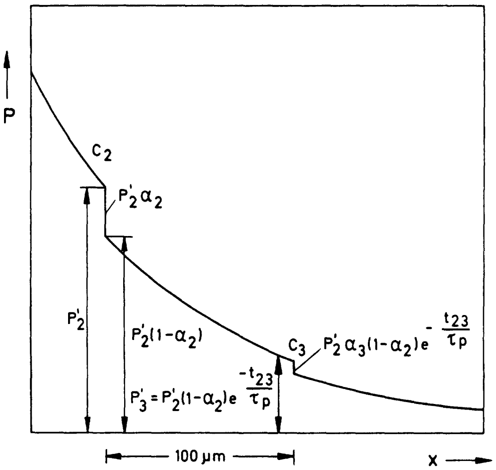


Fig. 10. Sketch indicating the amount of excess holes arriving at collectors C_2 and C_3.

$$Q_2(31V)/Q_2(11V) P_2'\alpha_2(31V)/P_2'\alpha_2(11V) = 1.3.$$

From the above equations we calculate the collector efficiencies at C_2 and find

$$\alpha_2(11V) = 0.23$$

and

$$\alpha_2(31V) = 0.30.$$

Since the bias voltage at C_3 is chosen to be 11 volts, we will assume that

$$\alpha_2(11V) = \alpha_3(11V) = 0.23.$$

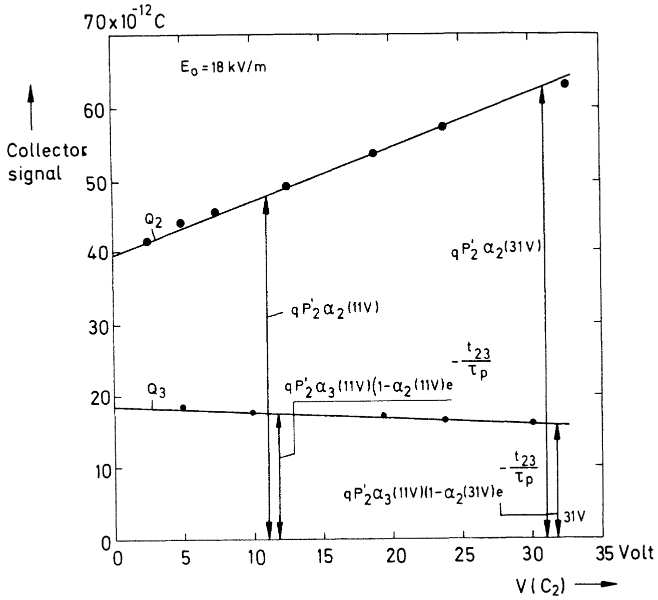


Fig. 11. Collector signals at C_2 and C_3 as a function of the bias voltage on C_2.

At 11 volts we find $Q_2(11\,V) = qP_2'\alpha_2(11\,V)$ is $48 \cdot 10^{-12}$C, and since $\alpha_2(11\,V)$ is 0.23 we find that qP_2' is $208 \cdot 10^{-12}$C. The signal at C_3 with a bias voltage of 11 volts on C_2 is

$$Q_3(11\,V) = qP_2'\alpha_3(1 - \alpha_2(11\,V)) \exp(-t_{23}/\tau_p) = 17.5 \text{ C},$$

so that

$$\exp - t_{23}/\tau_p = 0.475.$$

Since we measure that t_{23} = 120 ns, we find that

$$\tau_p = 90 \text{ ns}.$$

This small value is in reasonable agreement with values reported in the literature for silicon surfaces [10].

CONCLUSIONS

It is possible to use structures made in silicon by the standard integrated circuit planar technology to perform the Haynes-Shockley experiment. The addition of two extra collector contacts makes the accurate measurement of the hole mobility possible and allows a rough estimate of the diffusion coefficient D_p and the hole lifetime τ_p to be obtained. Since the structures can be easily fabricated and the peripheral electronic equipment is common in most university electronic laboratories, the experiment is very well suited to accompany an introductory course in semiconductor physics. Moreover, since the measurement results show unexpected deviations from simple theory, the structures are worthy of scrutinization by the more advanced students.

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An Approach to a Modest Digital Laboratory Adjunct for Logic Design Courses

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Abstract—**The Early Bird Courses leading to an MS degree at the University of Santa Clara cater to the student with a full-time job. This places severe time constraints for a laboratory adjunct. The program also possesses equipment constraints. A laboratory adjunct is described which meets these constraints, and provides the student with familiarization of TTL logic, motivation and reinforcement to the theory. Solderless breadboards are used, and four laboratory periods per quarter are held. The experiments are described.**

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INTRODUCTION

The graduate program in computer science at the University of Santa Clara is oriented towards the part-time student, via 2 unit "Early Bird" courses held from 7 a.m. to 9 a.m. once a week for a 10 week quarter. Students have backgrounds from related areas of study such as mathematics or electrical engineering, and a digital laboratory adjunct to logic courses is offered, since many of the students may otherwise never be exposed to actual logic devices. The Department of Electrical Engineering and Computer Science currently offers two such graduate courses as core requirements: EECS305 covers combinational logic and EECS306 covers sequential circuits.

The student should not be kept away from his full-time job for extended periods. This required innovative and easily checked laboratory assignments that could be performed in a minimal amount of time while still effectively demonstrating a particular concept. Equipment was constrained to ten Elite-3 solderless breadboards, which have an integral 5 volt supply, ten single pole double throw undebounced switches, four debounced pushbuttons, and twelve lamps. The equipment and

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