Measurement of Hole Mobility in Heavily Doped n-Type Silicon

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Abstract—**Accurate measurements of the mobility (and diffusion coefficient) of minority-carrier holes in Si:P with doping in the 10^{19} cm^{-3} range have been done. The technique employed the measurement of diffusion length by means of lateral bipolar transistors of varied base widths, and the measurement of minority-carrier lifetime on the same wafers from the time decay of luminescence radiation after excitation with a short laser pulse. Minority-carrier hole mobility is found to be about a factor of two higher than the mobility of holes as majority carriers in p-type Si of identical doping levels.**

I. INTRODUCTION

ALL BIPOLAR semiconductor devices employ heavily doped regions and minority-carrier transport in these regions often critically affects device performance. The gain and frequency response of bipolar transistors and the efficiency of silicon solar cells, for example, are intimately related to the minority-carrier lifetime, mobility, and bandgap narrowing in emitter, base, and contact regions. Of the three minority-carrier transport parameters [1], data on minority carrier mobility in heavily doped Si is the most scarce. For device modeling purposes, the minority (hole) mobility in heavily doped n-type Si is usually assumed to be identical to the corresponding (well characterized) majority-carrier (hole) mobility in heavily doped p-type Si [2]. However, theoretical treatments and some experimental results predict both higher and lower values for mobility of minority carriers [3], [4].

It has been shown from first principles [1] that a value of minority-carrier hole diffusion coefficient in n-type Si cannot be obtained solely from steady-state device measurements. Steady-state measurements can only provide values of the hole diffusion length L_p and the equilibrium hole concentration-diffusion coefficient product p_0D_p. An additional ac technique or time transient measurement is required to measure the minority-carrier lifetime τ_p. and allow the extraction of hole mobility μ_p. In the work reported here, these two measurements have been performed on the same wafer.

The most complete set of minority-carrier mobility measurements was made in the moderately doped (10^{17}–10^{19} cm^{-3}) range by Dziewior and Silber [5] using ac optical excitation of a photodiode-like structure, whose base was under investigation. Their results showed that the mobility of electrons in p-type Si resembled electron majority-carrier mobility. However, their data indicated that the mobility of holes in n-type Si appeared to be higher than for (majority) holes in p-type Si of the same doping, at least up to the 10^{19} cm^{-3} doping range. In this paper we extend the measurements of minority-carrier hole mobility in Si:P to doping levels approaching 10^{20} cm^{-3}, and provide an empirical fit for μ_p as a function of donor density N_D valid through this range.

II. EXPERIMENTAL

Epitaxially grown P-doped layers deposited on 0.2 Ω·cm ⟨100⟩ B-doped substrates were used in this investigation [6]. Three-in. wafers with epitaxial layer doping spanning the 10^{19} cm^{-3} doping range were studied. The epi-layer thicknesses ranged from 30 μm at the lower doping end to 5 μm at the higher doping. Sheet resistances, Hall mobilities, and junction depths were accurately measured, and the doping density N_D was extracted. Lateral p-n-p transistors (Fig. 1(a)) with base widths ranging from 2.5 to 11.25 μm were fabricated by implantation of a heavy dose B^+ for emitter and collector regions and implantation of P^+ for base contact regions. Metallization was Al:Si. Minority-carrier (hole) diffusion lengths L_p were extracted from plots of dc collector current versus base width [7].

In samples with heavily doped junctions, transient or ac electrical measurements that are able to yield accurate lifetimes of approximately 1 ns are extremely difficult to perform due to high junction capacitance and significant charge storage effects. As a result, the technique of minority-carrier lifetime measurement used here is optical. We measure the temporal decay of band-to-band photoluminescence radiation [8] after optical excitation by a 200-ps 647-nm Kr^+ ion laser pulse. Fig. 1(b) shows the experimental apparatus used. Pulses from the mode-locked laser were selected by a Bragg cell at 4 MHz and a single photon counting technique was employed to extract the decay of the photoluminescence intensity as a function of time after the arrival at the sample of the excitation laser pulse. The technique is described in detail in a recent monograph [9].

The incident laser excitation intensity was kept low so that the wafers were always low-level injected. As expected, the photoluminescence light intensity decayed exponentially with a time constant characteristic of the dominant (nonradiative) decay path. The lifetime measurement was performed on the full device wafers, at a location approximately 5 mm from the lateral transistors used to measure diffusion length.

III. RESULTS

The measured hole diffusion lengths are plotted (circles) in Fig. 2 as a function of epitaxial layer doping. The values are

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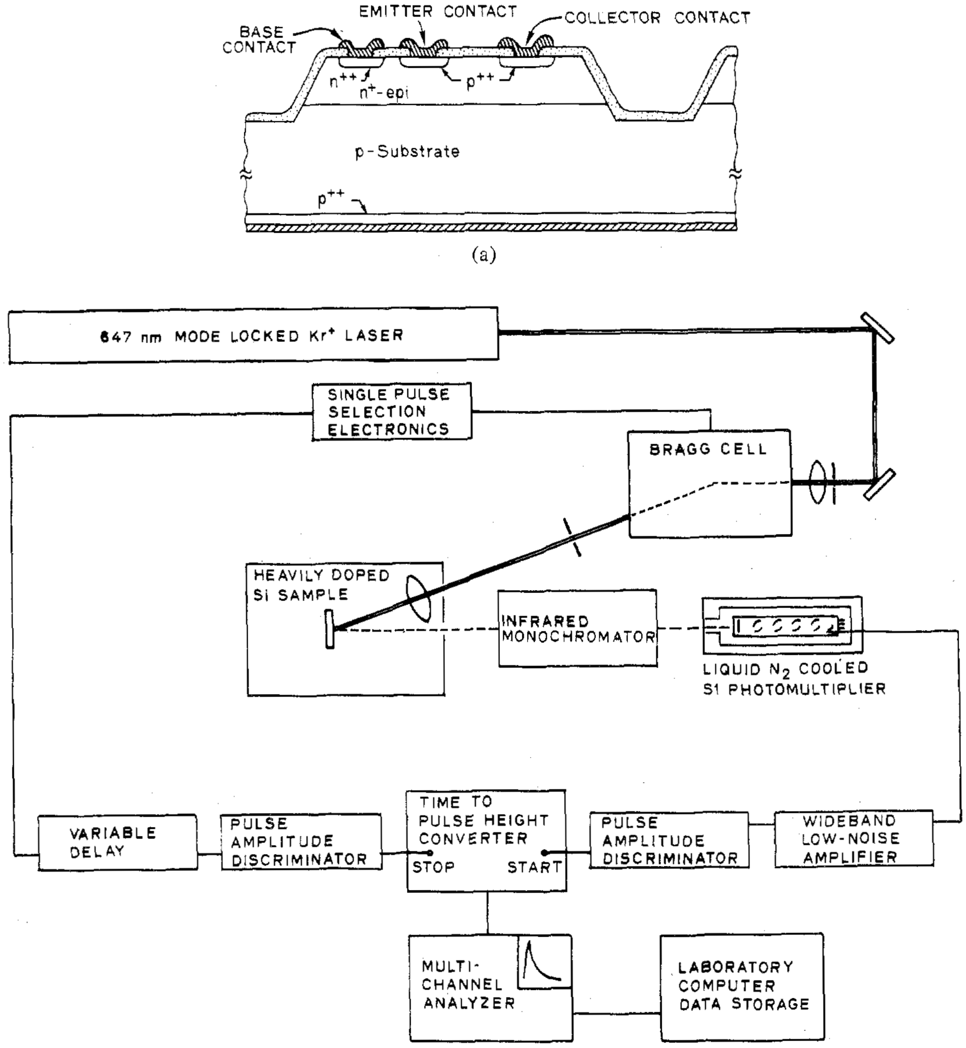

(a)

(b)

Fig. 1. (a) Cross section of lateral bipolar transistor used for L_p measurements. (b) Schematic of the apparatus used to measure minority hole lifetime.

consistent with other measurements of L_p [1], [7]. Experimental uncertainty in L_p determination is less than 10 percent for all samples. The diffusion-length measurements were made at 292 K.

Measurements of hole lifetime (solid squares) plotted as a function of epitaxial layer doping are also reported in Fig. 2. In addition, the bulk lifetime data of Dziewior and Schmid [8] (DS) is also plotted (boxes). Our data reproduce the strong doping dependence of τ_p reported previously, and agreement in lifetime values with the heavily-doped as-grown samples [8] is reasonable. Our lifetime measurements were made at 294 K. Because the measurements were performed on epitaxial layers, the signal-to-noise ratio was slightly degraded over that from bulk samples due to low-level luminescence from the substrate [10]. Nevertheless, uncertainty in lifetime is less than 6 percent for all samples.

It must be noted that the DS lifetime data comes from previously unprocessed doped-as-grown n-type (dopant unspecified) bulk Si without a passivation layer present. Our lifetime measurements were done on epi-layers that were subject to a number of high-temperature heat treatments in addition to the epitaxial growth. A grown oxide passivation layer was present to reduce effects due to surface recombination of minority carriers.

Fig. 3 plots the μ_p values extracted from the Fig. 2 data using

$$L_p = \sqrt{D_p \tau_p} \tag{1}$$

and

$$\mu_p = (q/kT) D_p. \tag{2}$$

The maximum error in the determination of μ_p is proportional to the square of the uncertainty in the L_p determination plus the uncertainty in τ_p determination—less than 25 percent for all data points reported. Also included in the plot is previously published data [4], [5], [11]. As discussed earlier (and in detail in [1]), we have restricted consideration to data that were obtained by using time-dependent techniques or a combination of steady-state measurements and time-dependent techniques. The solid circle plots a single data point that was obtained using a photoluminescence decay lifetime measurement tech-

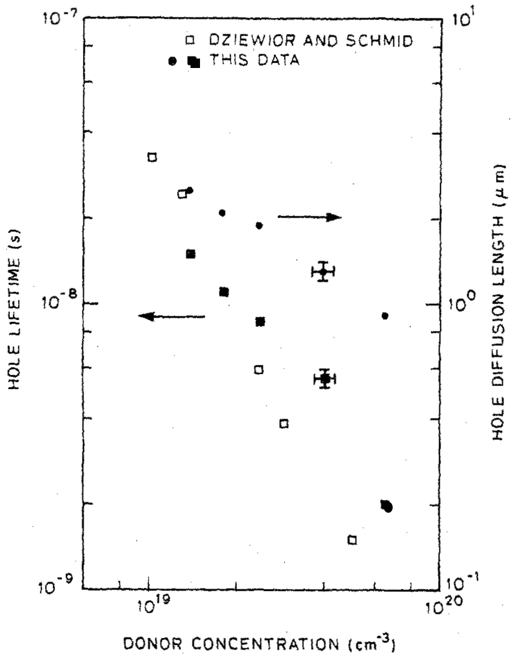

Fig. 2. Hole diffusion lengths L_p measured at T = 292 K from lateral bipolar transistors (circles) and minority hole lifetimes τ_p measured at T = 294 K in the base region of the lateral bipolar transistors (solid squares) plotted versus epitaxial layer (base) doping. Additional T = 300-K bulk Si lifetime data from [9] are also plotted (boxes).

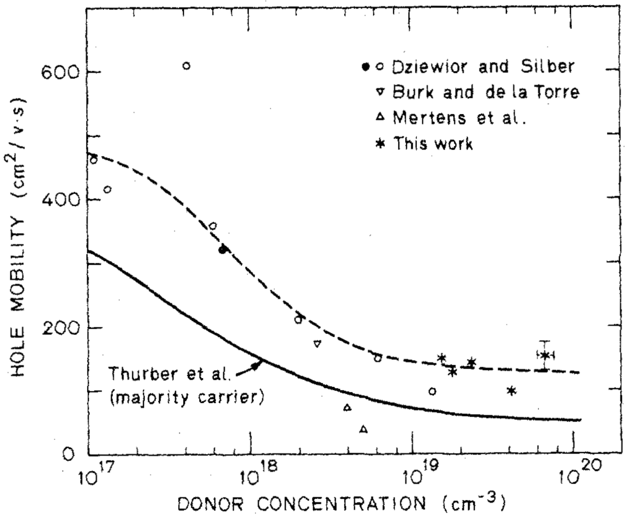

Fig. 3. Measured hole mobility plotted versus epitaxial layer doping. All data for T = 297 K.

TABLE I

sample	$N_D(cm^{-3})$	$L_p(\mu m)$	$\tau_p(ns)$	$\mu_p(cm^2/V.s)$
196 D1	1.4×10^{19}	2.47	15.3	155
198 D1	1.8×10^{19}	2.13	12.7	138
200 D1	2.4×10^{19}	1.88	8.7	157
202 D1	4.0×10^{19}	1.26	5.5	112
203 D1	6.5×10^{19}	0.92	2.0	167

nique as was used here. Table I lists the measured values of doping, diffusion length, hole lifetime, and the extracted mobility for the samples reported here.

In the 10^{19} cm^{-3} doping range investigated here, Fig. 3 reveals that the minority hole mobility at a given donor density is roughly twice the majority hole mobility at the same acceptor density. This date are consistent with the trend of the data in the lower doping range except for the points of Mertens *et al.* [11], whose extraction required a number of assumptions and the separation of various capacitance components. The extension of the mobility data to the 10^{19} doping range allows construction of a empirical best-fit for the mobility of minority holes as a function of donor density:

$$\mu_p = \frac{370}{1+\left(\dfrac{N_D}{8\times10^{17}}\right)^{1.25}} + 130 \text{ cm}^2/\text{V} \cdot \text{s}. \qquad (.3)$$

This fit is based upon the new data presented here for the higher doping range, and the data of [5] in the medium doping range down to 10^{17} cm^{-3}. In the low doping range, this fit incorporates the data of [12] and the more recent data of [13]. These both show that at very low doping densities, hole mobility is essentially identical in p-type and n-type Si. Below a donor doping of approximately 5 10^{15} cm^{-3}, this fit predicts minority and majority hole mobilities to be essentially equal. Some very recent data [14] disagree with this conclusion and with [12] and [13], and indicate that minority hole mobility is roughly 25 percent higher than majority hole mobility for all donor dopings below 5 10^{15} cm^{-3}.

In the high ($>10^{19}$ cm^{-3}) doping range, the new data presented here showing much higher mobility of holes as minority carriers than as majority carriers is in fair quantitative agreement with the theoretical calculations of Bennett [3]. His calculations, stated to be valid only in the 10^{19} cm^{-3} doping range, predict a minority-to-majority hole mobility ratio of approximately 2.8. This is slightly higher than the minority-to-majority hole mobility ratio of approximately 2.2 that we experimentally report here for similar doping densities.

These results have wide implications. They suggest that p-n-p bipolar transistors with high base dopings have the potential to be as fast (in base transit) as similar base-width n-p-n transistors—a symmetry that may be exploited with fast low-power complimentary bipolar logic. Furthermore, these measurements provide key information for the modeling of solar cell contact regions and bipolar transistor emitters, and they provide essential information for the accurate extraction of band gap narrowing in n-type Si.

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REFERENCES

[1] J. del Alamo, S. Swirhun, and R. M. Swanson, "Measurement and modeling of minority carrier transport in heavily-doped silicon," *Solid-State Electron.* vol. 28, pp. 47–52, 1985.

[2] W. R. Thurber, R. L. Mattis, Y. M. Liu, and J. J. Filliben, "Resistivity-dopant density relationship for boron-doped silicon," *J. Electrochem. Soc.*, vol. 127, pp. 2291–2295, 1980.

[3] H. S. Bennett, "Hole and electron mobilities in heavily-doped silicon: Comparison of theory and experiment," *Solid-State Electron.*, vol. 26, pp. 1157–1161, 1983.

[4] D. E. Burk and V. de la Torre, "An empirical fit to minority hole mobilities," *IEEE Electron Device Lett.*, vol. EDL-5, pp. 231–233, 1985.

[5] J. Dziewior and D. Silber, "Minority-carrier diffusion coefficients in highly-doped silicon," *Appl. Phys. Lett.*, vol. 35, pp. 170–172, 1979.

[6] J. del Alamo and R. M. Swanson, "Fabrication and characterization of epitaxial heavily-doped silicon," *J. Electrochem. Soc.*, vol. 132, pp. 3011-3016, 1985.

[7] A. Wieder, "Emitter effects in shallow bipolar devices: Measurements and consequences," *IEEE Trans. Electron Devices,* vol. ED-27, pp. 1402–1409, 1980.

[8] J. Dziewior and W. Schmid, "Auger coefficients for highly-doped and highly-excited silicon," *Appl. Phys. Lett.*, vol. 31, pp. 346–348, 1977.

[9] J. N. Demas, *Excited State Lifetime Measurements.* New York: Academic, 1983.

[10] S. E. Swirhun, R. A. Sinton, and R. M. Swanson, "Measurements of minority carrier lifetime in heavily-doped silicon," in preparation.

[11] R. Mertens, J. Van Meerbergen, J. Nijs, and R. Van Overstraeten, "Measurement of the minority-carrier transport parameters in heavily-doped silicon," *IEEE Trans. Electron Devices,* vol. ED-27, pp. 949–955, 1980.

[12] J. Muller, H. Bernt, and H. Reichl, "Measurement of minority carrier lifetime and diffusion length in silicon epitaxial layers by means of the photocurrent technique," *Solid-State Electron.*, vol. 21, pp. 999-1003, 1978.

[13] D. Gasquet, J. P. Nougier, and G. Gineste, "Determination of transport coefficients by transient photoconductivity experiments," *Physica,* vol. 129B, pp. 524-526, 1985.

[14] A. Neugroschel, "Minority-carrier diffusion coefficients and mobilities in Silicon," *IEEE Electron Device Lett.*, vol. EDL-6, pp. 425–428, 1985.