

SIMULTANEOUS MEASUREMENT OF HOLE LIFETIME, HOLE MOBILITY AND BANDGAP NARROWING IN HEAVILY DOPED n-TYPE SILICON¹

J. del Alamo, S. Swirhun, and R. M. Swanson

Solid State Electronics Laboratory, Stanford University
Stanford, CA 94305

ABSTRACT

The hole diffusion length, hole lifetime, hole mobility, and hole equilibrium concentration in epitaxial heavily phosphorus-doped silicon have been measured by a combination of steady-state and transient techniques. Steady state measurements were performed on bipolar transistors in which the base was epitaxially grown. The transient measurement relied on the observation of the decay of the photoluminescence radiation after laser excitation. Significant findings are: 1) the hole mobility is about a factor of two larger in heavily doped n-type silicon than in p-type silicon; 2) the apparent bandgap narrowing is smaller than previously thought, with a value of about 90 meV at a doping level of 10^{20} cm^{-3} .

INTRODUCTION

The knowledge of the minority carrier transport parameters in heavily doped silicon is required for the physical understanding, accurate modelling, and optimization of such fundamental parameters as the gain of bipolar transistors, and the efficiency of solar cells.

In lowly doped semiconductors, the product of the equilibrium hole and electron concentrations (p_o and n_o , respectively) is a constant that depends only on temperature:

$$p_o n_o = n_{i0}^2(T), \quad (1)$$

where n_{i0} is the intrinsic carrier concentration.

Drastic changes occur in the band structure of n-type silicon as more donors are introduced. Their net physical effect is the increase of the $n_o p_o$ product. In other words, if we introduce a large amount of electrons, N_D , the resulting hole concentration in equilibrium is given by $p_o = n_{ie}^2(T, N_D)/N_D$, where $n_{ie} > n_{i0}$. Therefore, p_o in heavily doped silicon is higher than what is expected by the low-doping relationship (1).

Since n_{i0} depends exponentially on the bandgap of the semiconductor, a popular way to mathematically treat the problem consists of assuming that a rigid narrowing of the bandgap is solely responsible for the increase of p_o , such that

$$p_o N_D = n_{ie}^2(N_D, T) = n_{i0}^2(T) \exp \frac{\Delta E_g^{app}(N_D, T)}{kT}, \quad (2)$$

where ΔE_g^{app} represents the fictitious bandgap shrinkage that would account for the increase of p_o if no other heavy doping effects occurred.

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In addition to the equilibrium concentration of holes, two more parameters are relevant for the understanding of hole transport in a n-type semiconductor: the lifetime, τ_p , and the mobility, μ_p . In n-Si both of these parameters are strongly affected by high concentrations of donor impurities.

Although several authors have measured the transport parameters in n-type silicon at high doping levels, discrepancies of more than one order of magnitude are present among the values of τ_p , μ_p , and p_o reported by different authors [1]. Most of these discrepancies arise from the fact that steady-state measurements only provide values of the hole diffusion length, L_p , and $p_o D_p$, the equilibrium hole concentration-diffusion coefficient product ($D_p = (kT/q)\mu_p$, $L_p = \sqrt{D_p \tau_p}$) [1]. An additional time-transient technique is required to measure τ_p , and therefore obtain μ_p and p_o .

The description of a systematic experiment that simultaneously performs steady-state and time-transient measurements is the subject of this paper.

EXPERIMENTAL

Fig. 1 shows a cross section of the devices fabricated. On a (100) B-doped 0.2-0.5 $\Omega \cdot \text{cm}$ substrate a n^+ -epitaxial layer is grown in a $\text{SiH}_4/\text{PH}_3/\text{H}_2$ system at 1050°C [2]. From a majority carrier point of view, the epitaxial material is essentially identical to as-grown, diffused, and ion-implanted silicon of similar doping level [3]. Front p^{++} , n^{++} , and back p^{++} -regions were formed by B^+ implantation, P diffusion and BF_2^+ implantation, respectively, followed by a simultaneous thermal step at 1050°C . The devices are isolated from each other by means of trenches.

In Fig. 1, the top device is a $p - n^+ - p^{++}$ bipolar transistor in the vertical direction. From the collector characteristics of this device working in the upward mode, the parameter $p_o D_p$ in the n^+ -epitaxial base is extracted. To separate the area-related component from the total collector current, three devices with different collector areas were integrated on the same chip.

The bottom device of Fig. 1 shows a $p^{++} - n^+ - p^{++}$ lateral bipolar transistor along the surface of the epitaxial region. By simultaneously fabricating several lateral transistors with different lateral base widths, the diffusion length of holes in the epitaxial base can be obtained [4].

The following measurements were performed at room temperature:

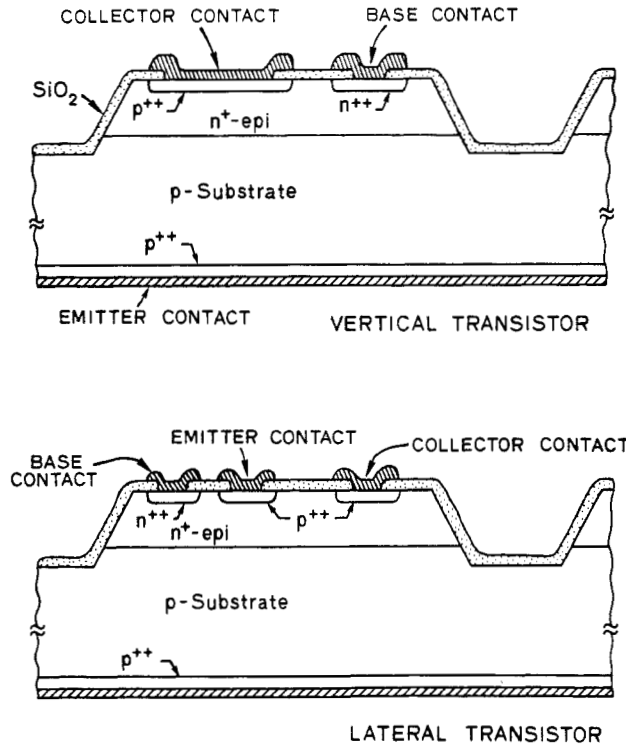


Fig. 1: Schematic cross section of vertical and lateral bipolar transistors.

Measurement of N_D

The sheet resistance and the Hall mobility were measured in an integrated van der Pauw structure. The vertical carrier concentration profile and epitaxial layer thickness were obtained by spreading resistance. Fig. 2 shows a typical example. The value of the Hall scattering factor was taken into consideration [5]. The typical error in N_D is around 10%.

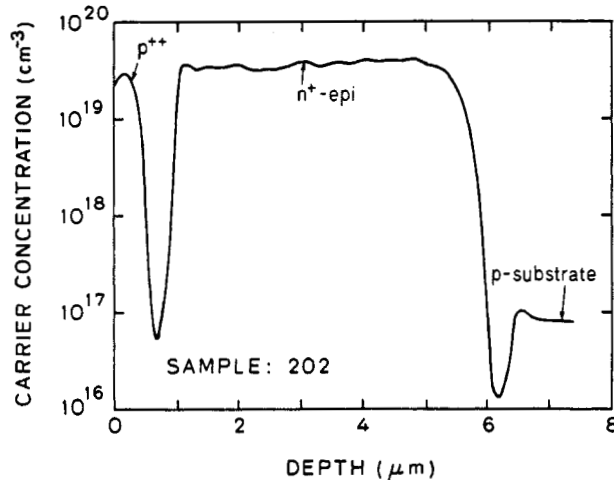


Fig. 2: Carrier concentration profile of a vertical bipolar transistor obtained by spreading resistance.

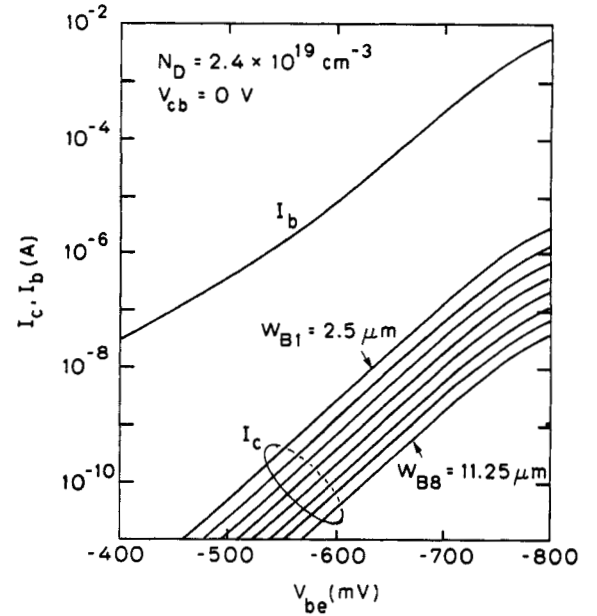


Fig. 3: I-V characteristics of a set of lateral transistors.

Measurement of L_p

Fig. 3 shows the I-V characteristics of a typical set of lateral bipolar transistors with a common base contact. The lateral basewidth changes from device to device in increments of 1.25 μm . L_p is extracted in a manner essentially identical to Wieder [4], with less than 10% error.

Measurement of $p_o D_p$

Fig. 4 shows the I-V characteristics of the vertical bipolar transistors. While the base current has strong non-idealities, the collector current is ideal for all three devices. The area-related collector current density is:

$$J_{oc} = q p_o D_p \frac{1}{L_p} \frac{1}{\sinh \frac{W_B}{L_p}}, \quad (3)$$

where W_B indicates the vertical base width. If $W_B \leq L_p$, then

$$J_{oc} = q p_o D_p \frac{1}{W_B}. \quad (4)$$

This is the ideal mode of operation for the extraction of $p_o D_p$. The typical error in $p_o D_p$ in this regime is about 10%.

The condition $W_B \leq L_p$ is difficult to fulfill if L_p is of the order of 2 μm or less. Therefore, for doping levels higher than around $2 \times 10^{19} \text{ cm}^{-3}$, the use of the exact Eq. 3 is required. In this case, L_p is determined from the lateral transistors that are located at an average distance of 2 mm from the vertical transistors. The error in $p_o D_p$ in this regime is about 25%.

Measurement of τ_p

τ_p is extracted from the time decay of the emitted band-to-band photoluminescence radiation after the wafer is excited by a 200 ps Kr^+ ion laser pulse [6]. Pulses from the mode-locked laser were selected by a Bragg cell at 4 MHz. Due to the extremely small

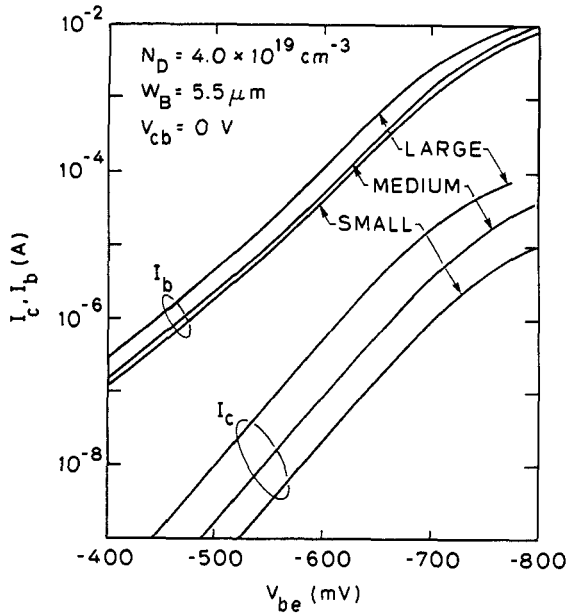


Fig. 4: I-V characteristics of three vertical transistors of different sizes.

photoluminescence efficiency, a single photon counting technique was employed [7]. The detector consists of a liquid N_2 cooled S-1 photomultiplier. The measurements were performed on the van der Pauw structure at an average distance of 5 mm from the bipolar devices. The error in τ_p is less than 6%.

RESULTS AND DISCUSSION

Fig. 5 collects the measurements of hole diffusion length. L_p is a strong function of doping. The values here reported and those of other authors (summarized in [1]) are in agreement within a factor of two.

Fig. 6 shows the measurements of lifetime. The stars represent measurements carried out on the device wafers, while the open circles are measurements performed on other epitaxial wafers and as-grown substrates. The data here reported and those obtained by other authors by time-transient techniques [1] are in agreement within a factor of two to three. A fit that describes the total set of lifetime data is:

$$\frac{1}{\tau_p} = 7.8 \times 10^{-13} N_D + 1.8 \times 10^{-31} N_D^2 \text{ s}^{-1}. \quad (5)$$

On those samples in which simultaneous measurements of lifetime and diffusion length were performed, D_p and μ_p can be deduced. Fig. 7 collects the values of μ_p , together with those of other authors [8],[9],[10]. Fig. 7 reveals that the hole mobility in n-type silicon, as a minority carrier, is about two times larger than as a majority carrier in p-type silicon[11]. This result, theoretically predicted by Bennett [12], is not only important for modelling purposes, but it implies that pnp bipolar transistors are potentially as fast as current npn devices. This finding opens the possibility of very fast, low power complementary silicon bipolar logic. A fit to the available measurements of μ_p is:

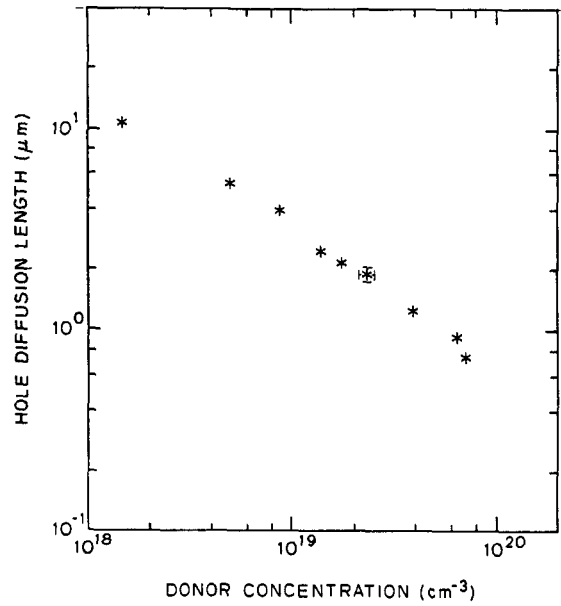


Fig. 5: Measured hole diffusion length versus doping level ($T=292$ K).

$$\mu_p = \frac{370}{1 + \left(\frac{N_D}{8 \times 10^{17}}\right)^{1.25}} + 130 \text{ cm}^2/\text{V.s}, \quad (6)$$

where a recent measurement of Gasquet et al. [13] at very low doping levels has been taken into consideration.

For those wafers in which measurements of μ_p have been performed, the value of p_o was extracted from the measurement of $p_o D_p$. For the other wafers, the fit described by Eq. 6 was used. The resulting values of p_o are plotted in Fig. 8. The solid line in Fig. 8 represents the theoretical calculation of p_o without considering heavy doping effects (with the correct Fermi-Dirac statistics). The experimental measurements reported here deviate from the low doping theory at a doping level of about

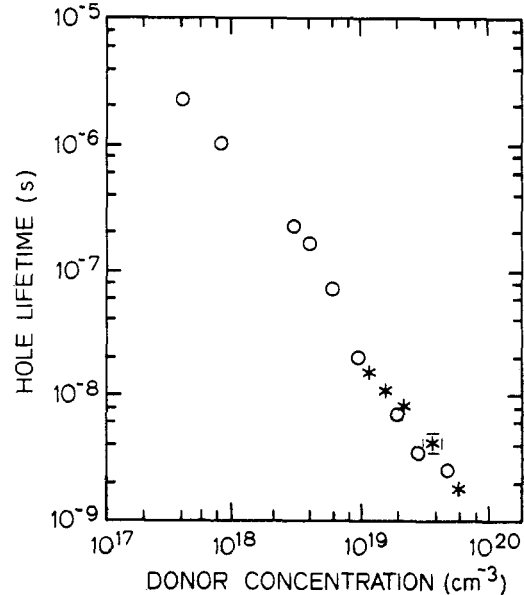


Fig. 6: Measured hole lifetime versus doping level.

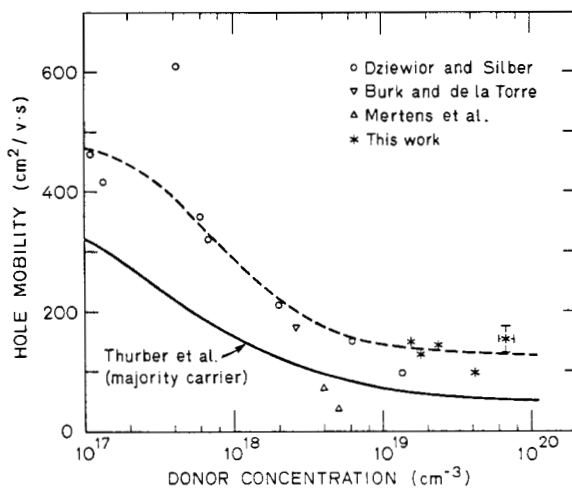


Fig. 7: Measured hole mobility versus doping level in this work and by other authors.

$7 \times 10^{17} \text{ cm}^{-3}$. The dashed line is a calculation that includes the rigid bandgap narrowing measured recently by photoluminescence [14]. This last calculation gives a better agreement to the experimental data. However, the fact that it is systematically 30 to 50% lower than the measured results may indicate the occurrence of a tail at the top of the valence band.

For the purpose of device modelling, we plot in Fig. 9 the extracted value of ΔE_g^{app} defined by Eq. 2. The data from other authors, reinterpreted as argued in [1], has been included [4],[10],[15],[16]. A fit that describes the collection of points is:

$$\Delta E_g^{app} = 18.7 \times 10^{-3} \ln \frac{N_D}{7 \times 10^{17}} \text{ eV}, \quad (7)$$

for $N_D \geq 7 \times 10^{17} \text{ cm}^{-3}$, and zero at lower doping levels.

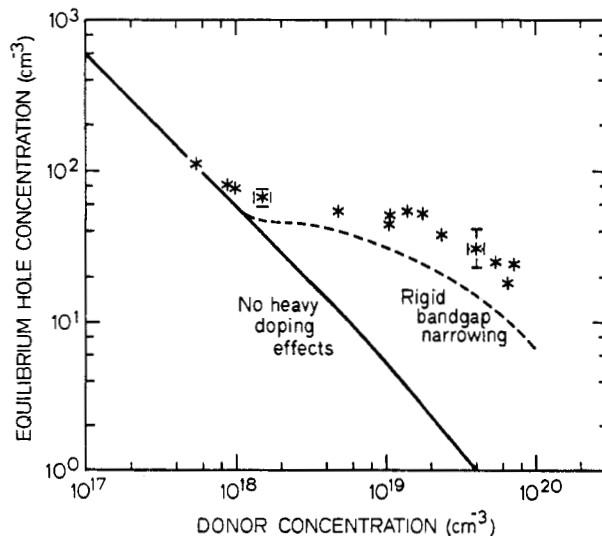


Fig. 8: Measured equilibrium hole concentration versus doping level ($T=292 \text{ K}$). The lines represent theoretical calculations.

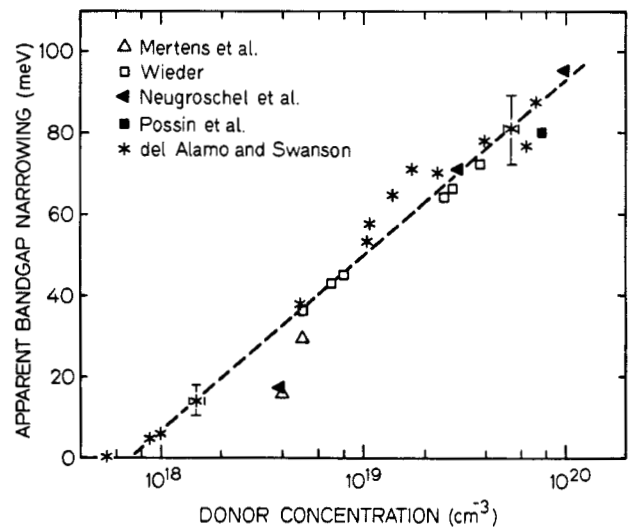


Fig. 9: Apparent bandgap narrowing versus doping level.

CONCLUSIONS

Simultaneous measurements of hole lifetime, hole mobility, and hole equilibrium concentration have been carried out in heavily phosphorus doped silicon that was grown by epitaxy. Fits to the parameters are given for device modelling purposes.

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