MEASUREMENT OF ELECTRON LIFETIME, ELECTRON MOBILITY AND BAND-GAP NARROWING IN HEAVILY DOPED p-TYPE SILICON

S. E. Swirhun, Y.-H. Kwark and R. M. Swanson

Solid State Electronics Laboratory, Stanford University
Stanford CA., 94305

ABSTRACT

The parameters that control the transport of minority carriers in heavily doped Si:B have been measured by a combination of steady state electrical and transient optical techniques. Electron diffusion length and electron lifetime measurements have been conducted on doped-as-grown wafers to extract the minority carrier electron mobility as a function of acceptor doping density. Effective band-gap narrowing in p^+ epitaxial layers has been characterized using bipolar test structures. Significant findings: 1) the electron mobility is about 2.5 times larger in heavily doped p-type Si than in n-type. 2) bandgap narrowing exceeds 120 meV at $N_A = 2 \times 10^{20}$ cm^{-3}. 3) minority electron lifetime in processed p^+ Si is not well modeled over a large doping range by an "Auger" coefficient.

INTRODUCTION

All semiconductor devices use heavily doped regions. Knowledge of the fundamental parameters that characterize the transport of minority carriers in these heavily doped regions is required for modeling existing bipolar devices and essential for the development of higher performance designs. Three parameters allows a complete description of minority carrier transport in heavily doped Si; the minority carrier lifetime τ, the minority carrier mobility μ and the effective equiblibrium minority carrier density n_o (or p_o).

Most experiments to characterize minority carrier transport in heavily doped Si have addressed n-type material [1,2]. In the published literature there is only a single experimental determination [3] of minority electron mobility $\mu_n(N_A)$ in the moderate doping range and no data above 10^{19}. Of the few measurements [4,5] of minority electron lifetime $\tau_n(N_A)$ some show order-of-magnitude variations, perhaps due to the fact that some of the experiments measure diffusion length L_n ($L_n = \sqrt{(kT/q)\tau_n\mu_n}$) and assume μ_n values. As for band-gap narrowing, only a single published reference addresses [6] it in p^+ Si.

The relation we use here between the value of the equilibrium minority carrier density n_o (the physical parameter describing heavy doping effects) and the apparent band-gap narrowing ΔE_G (the model parameter) deserves discussion. As acceptor doping increases above 10^{17} the Si band structure changes due to the appearance of band-tails and an impurity band, the merging of the impurity band with the valence band, and modification of the density of states. The net effect of these changes is an increase in the equilibrium carrier concentration product $n_o p_o = n_{ie}^2(N_A, T)$ over $n_{io}^2(T)$, the square of the low doping intrinsic carrier density. Since the majority carrier density $p_o = N_A^- \approx N_A$ is determined by the acceptor concentration N_A, this is equivalent to saying that heavy doping effects increase the minority carrier density over what would be expected in low doped material. Alternatively, we can describe the heavy-doping modified equilibrium minority carrier density $n_o(N_A, T)$ by introducing a ficticious model parameter $\Delta E_G(N_A, T)$ that is assumed to cause a rigid narrowing of the bandgap, and encompass all heavy doping effects:

$$n_o N_A = n_{ie}^2(N_A, T) = n_{io}^2(T) exp \frac{\Delta E_G(N_A, T)}{kT}$$

EXPERIMENTAL

The experimental work was done in two parts. On bulk doped-as-grown Si:B wafers with dopings from 10^{17} to 10^{20} cm^{-3} minority carrier lifetime τ_n was measured by monitoring the transient decay of luminescence after brief laser light excitation. Some of the identical wafers used for τ_n determination were selected for measurement of μ_n; lateral bipolar transistors were fabricated and L_n was extracted thereby allowing a determination of μ_n.

In the second part of the investigation $\Delta E_G(N_A)$ in p^+ Si:B epitaxial layers was measured. The technique requires the fabrication of both lateral and vertical transistors with p^+ Si:B epitaxial base regions. Accurate ΔE_G values can be extracted even when base doping exceeds 10^{20} cm^{-3}.

Fig. 1 shows a cross section of a single lateral bipolar transistor diffusion length (L_n) test structure fabricated in bulk p^+ Si:B. In plan-view, the test structure has long stripe emitter and base contacts with several collectors spaced at lateral base widths W_B varying from 1.25 to 40 μm.

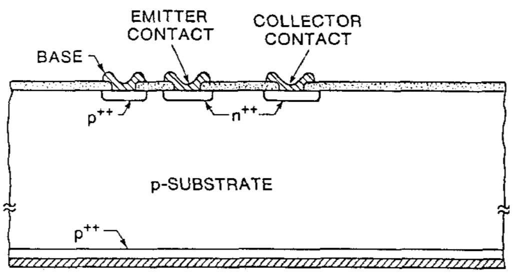

Fig. 1 Lateral bipolar transistor in bulk p^+ Si:B for L_n determination.

Emitter/collector and base regions were formed by $POCl_3$ diffusion and BF_2^+ implantation respectively.

Fig. 2 shows the block diagram of the minority lifetime measurement apparatus [7,4]. 200 ps laser pulses (at 1 MHz) from the Kr^+ ion laser are directed by the Bragg cell to strike the bulk p^+ Si sample and create electron-hole pairs, some of which recombine radiatively. The time decay of the luminescence radiation, as observed by a liquid N_2 cooled photomultiplier tube is used to monitor the time decay of the minority carriers in the sample, and hence yeild the minority carrier lifetime τ_n. The complicating factor here is that Si luminescence is extremely weak, and detection of 1 eV radiation is difficult. For this reason, the experiment is conducted in the "single photon mode" in which the time from the arrival at the sample of the laser pulse to the time of the emmision of the first detected luminescent photon is recorded. The electronic functions in Fig. 2 allow a spectrum of these "photon emmission delay times" to be collected.

In Fig. 3 cross-sections of the devices fabricated for $\Delta E_G(N_A)$ measurement are shown. On <111> 0.05 Ω cm Sb doped substrates p^+ epitaxial layers from 5 to 43 μm were grown. Most were grown using $H_2/SiH_4/B_2H_6$ at

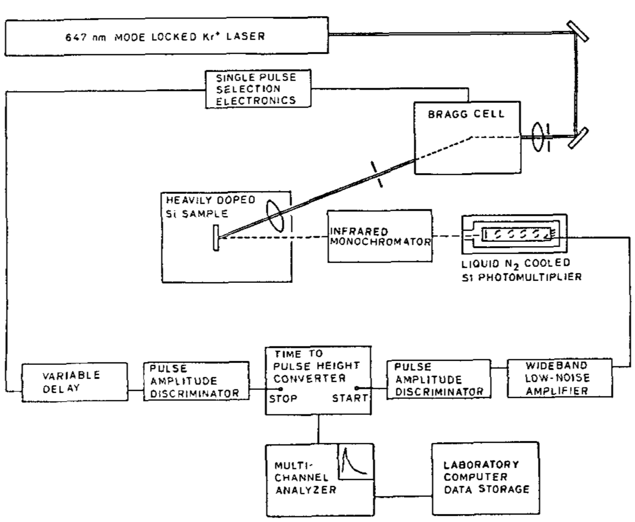

Fig. 2 Photoluminescence decay lifetime measurement apparatus.

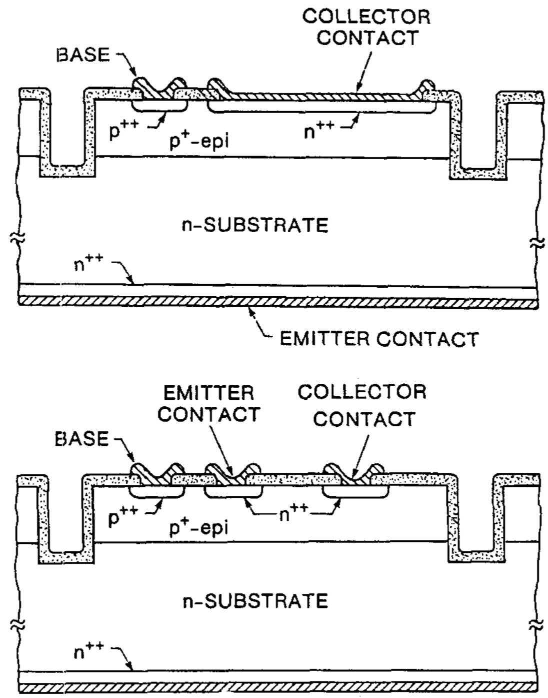

Fig. 3 Cross section of vertical and lateral bipolar transistors with p^+ epitaxial base region.

1050 C. Front and back contact regions were fabricated with $POCl_3$ diffusion and B^+ implantation. Isolation trenches were plasma etched.

The lateral npn transistor is used to extract the diffusion length L_n' for minority electrons [8,2] in the p^+ epi-layer, as described above for bulk p^+ material. Then, the collector current of the vertical npn transistor [6,2] in Fig. 3 may be used to extract the parameter product $n_o\mu_n$ of the p^+ epitaxial base layer, and since $\mu_n(N_A)$ is known from the bulk samples we obtain n_o (or equivalently ΔE_G). To remove the parasitic effects due to the collector perimeter, vertical transistors with different area-to-perimeter ratios were fabricated.

All measurements detailed below were done at 295 K.

Measurement of N_A In both the bulk p^+ samples and the p^+ epi-layers, sheet resistance and Hall mobility [9] were measured on square Van der Pauw structures immediately adjacent to the device area. The vertical carrier concentration profile and junction depth of the epi layers was measured by spreading resistance profiling. For all epi material, vertical doping variations were small and epi-substrate junctions abrupt. N_A accuracy is about 3%.

Measurement of L_n Lateral bipolar transistors with base widths (W_B) ranging from 1.25 to 40 μm were fabricated in the bulk p^+ material. The collector and base characteristics fo one such sample are illustrated in Fig. 4. L_n is extracted by fitting values of the collector current (at a specific V_{be}) as a function of W_B to an exponential as described in [8]. Accuracy is better than 7 %.

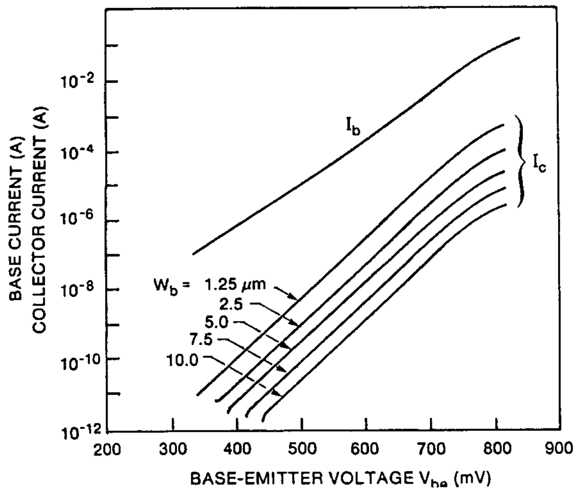

Fig. 4 I-V characteristics of lateral transistor L_n test structure; base doping 9.5 $\times 10^{18}$ cm^{-3}, $V_{cb} = 0$ V.

Measurement of τ_n Typical data from the photoluminescence lifetime experiment [7] are shown in Fig. 5. Time advances from left to right in 1 ns/channel increments. The peak at the right of the figure corresponds to the time of arrival at the p$^+$ sample of the incident laser pulse. The exponential photoluminescence intensity decay ($I(t) \propto exp - (t/\tau_n)$) can be accurately fit to extract lifetimes in all cases with accuracy better than 10 %.

Measurement of $n_o\mu_n$ The base and collector characteristics of the vertical bipolar transistor fabricated in p$^+$ epi material are illustrated in Fig. 6. The collector saturation current density is:

$$J_{oc} = kT\frac{n_o\mu_n}{L_n' sinh(W_B/L_n')}\ A/cm^2$$

where L_n' is the minority carrier diffusion length in the epi material measured by lateral p$^+$ epi-layer transistors as described above, and W_B is the vertical basewidth. The J_{oc} expression is simpler when $W_B < L_n$, but it is difficult to make $W_B \leq L_n$ for doping above 10^{19} cm^{-3}. In addition, L_n' measurements from lateral transistors are inaccurate when the epi-layer thickness is less than a few diffusion lengths.

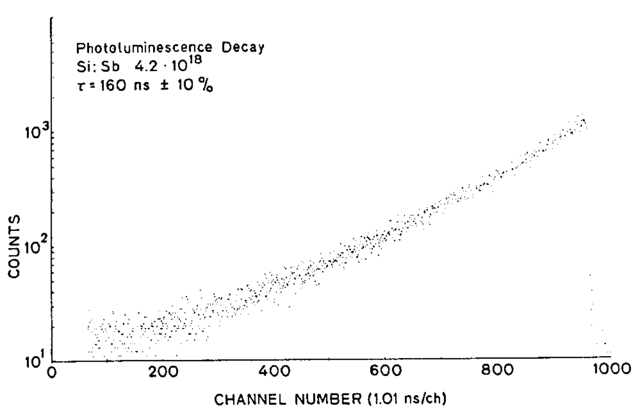

Fig. 5 Experimental data from photoluminescence decay lifetime experiment showing exponential decay $\propto exp - (t/\tau)$.

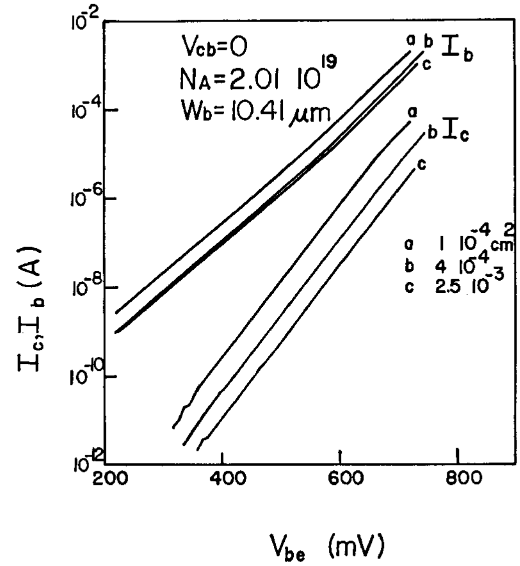

Fig. 6 I-V characterics of three vertical transistors with p$^+$ epitaxial base regions doped 2.01 $\times 10^{19}$ cm^{-3}.

RESULTS AND DISCUSSION

Fig. 7 shows the measurements of lifetime carried out on bulk p$^+$ samples. In the doping range above roughly 5 $\times$ 10^{18} cm^{-3} the data are consistent with previous direct lifetime measurements [4] in unprocessed material, and are

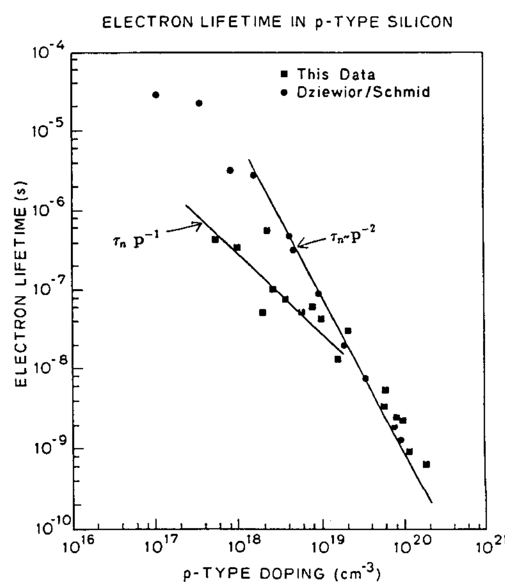

Fig. 7 Minority electron lifetime versus acceptor doping density.

2.2

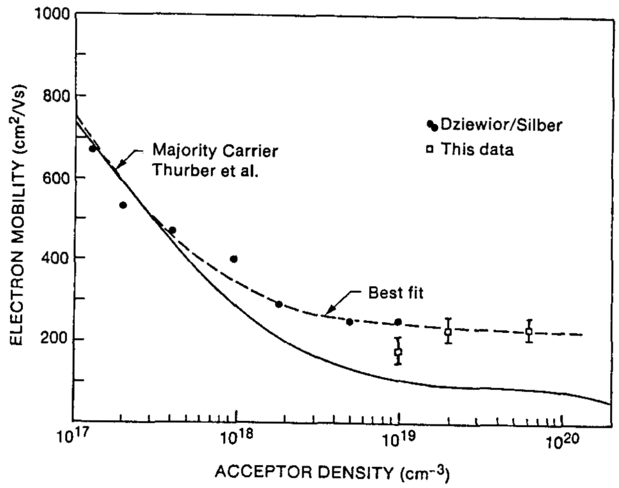

Fig. 8 Electron mobility in p-type bulk Si versus doping (points) and the best fit (dotted line); electron mobility in n-type Si (solid line).

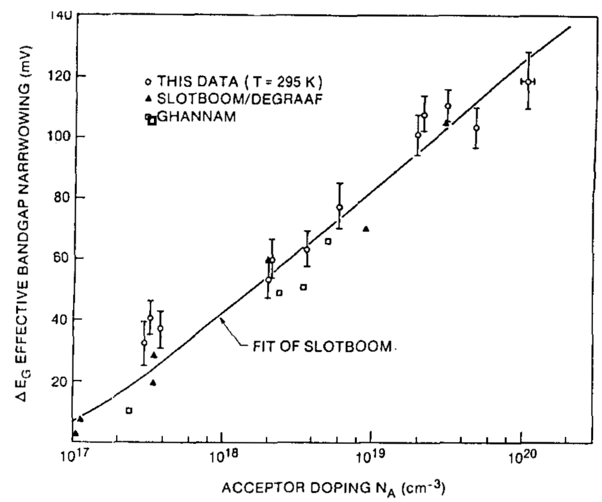

Fig. 9 Apparent band-gap narrowing versus doping density.

reasonably well described by an "Auger-like" N_A^{-2} dependence. At lower dopings however, $\tau_n \propto N_A^{-1}$. This data is the first direct τ_n measurement in *processed* p$^+$ Si, and it suggests that for modeling purposes the (normally used) 6 decade N_A^{-2} lifetime dependence may be better replaced by:

$$\tau_n^{-1} = 3.45 \times 10^{-12} N_A + 0.95 \times 10^{-31} N_A^2 \ s^{-1}$$

On bulk p$^+$ samples in which diffusion length L_n was measured, μ_n may be extracted since $L_n = \sqrt{(kT/q)\mu_n \tau_n}$. Fig. 8 plots $\mu_n(N_A)$ values obtained here and those for a lower doping reported elsewhere [3]. Fig. 8 shows that the (minority) electron mobility in p$^+$ Si is about 2.5 times larger than the majority electron mobility in n$^+$ Si [9]. A minority electron mobility enhancement 20 % over the majority value has been predicted theoretically [10]. This data, when combined with other measurements of minority electron mobility [11] at lower dopings has allowed the construction of a fit to μ_n at T=295 K:

$$\mu_n = 232 + \frac{1180}{(1 + (\frac{N_A}{8 \times 10^{16}})^{0.9})} \ cm^2 V^{-1} s^{-1}$$

Using the μ_n values from this fit and the measurements from transistors with p$^+$ epitaxial bases we are able to construct (Fig. 9) a plot of effective bandgap narrowing versus N_A.

Also included are the data of Slotboom and de Graaf [6] and Ghannam [13], both of which rely on the temperature independence of ΔE_G for their extraction. This agreement suggests that ΔE_G isn't strongly temperature dependent near 295 K. The best fit to ΔE_G suggested by Slotboom et al appears adequate, even in excess of 10^{20} cm^{-3} doping:

$$\Delta E_G(N_A) = 9 \times 10^{-3}(F + \sqrt{F^2 + 0.5}) \ eV$$

where $F = ln(N_A/10^{17})$. A comparison of $\Delta E_G(N_A)$ to an empirical best fit of $\Delta E_G(N_D)$ [1] would show approximately 25 meV more band-gap narrowing in Si:B than in equivalently doped n-type Si.

CONCLUSIONS

Measurements of electron lifetime, electron mobility and band-gap narrowing in p$^+$ Si:B have been carried out, and the fits describing the doping dependence of these parameters at 295 K have been constructed.

REFERENCES

1. J. del Alamo, S. Swirhun and R. M. Swanson, IEDM Tech. Digest, 1985, p290.
2. J. del Alamo, S. Swirhun and R. M. Swanson, Solid-St. Electron., **28**, p47, (1985).
3. J. Dziewior and D. Silber, Appl. Phys. Lett., **35**, p170, (1979).
4. J. Dziewior and W. Schmid, Appl. Phys. Letts., **31**, p346, (1977).
5. L. Passari and E. Susi, Jour. Appl. Phys., **54**, p3935, (1983).
6. J. W. Slotboom and H. C. de Graaf, Solid-St. Electron., **19**, p857, (1976).
7. S. E. Swirhun and R. M. Swanson, to be published.
8. A. Wieder, IEEE Trans. Electr. Dev., **ED-27**, p1402, (1980).
9. W. R. Thurber, R. L. Mattis, Y. M. Liu and J. J. Filliben, National Bureau of Standards publication NBS SP 400-64, May 1981.
10. H. S. Bennett, Solid-St. Electron., **28**, p25, (1985).
11. A. Neugroschel, IEEE Electr. Dev. Letts., **EDL-6**, p.425, (1985).
12. M. Ghannam, Ph.D. Dissertation, Katholieke Universiteit Leuven, 1985.