MEASUREMENT OF THE EMITTER SATURATION CURRENT BY A CONTACTLESS PHOTOCONDUCTIVITY DECAY METHOD

D. E. Kane, R. M. Swanson

Stanford Electronics Laboratories, McCullough 204
Stanford, CA 94305 (415)-497-4766

ABSTRACT

A novel method for the measurement of the saturation current of emitters is described. The transient decay of photogenerated carriers is measured on a lightly doped sample containing the emitter profile of interest. In high level injection, the recombination rate from the emitter is proportional to the square of the carrier concentration, so it can be separated from the linear bulk and surface recombination. Since no ohmic connections are required, this technique is uniquely suited to the study of passivated emitters. Furthermore, the emitter saturation current of a given profile can be measured both with and without a passivation layer, so that the relative sources of emitter recombination can be determined.

The measurement has been successfully performed on a variety of phosphorous and boron emitters. These results are presented.

INTRODUCTION

In silicon solar cells, the heavily-doped emitter regions, characterized by the emitter saturation current, J_{0E}, are a major source of recombination which limits the open-circuit voltage and hence efficiency attainable. Today, there are several novel methods of J_{0E} reduction being considered [1,2,3]. Reliable measurements of this parameter are necessary to achieve an optimization.

There are three conventional means of measuring J_{0E} of an emitter region. The first is to measure the total dark current of a solar cell, and to substract from it a value for the base recombination. The second involves performing a set of open-circuit voltage and short-circuit current decay measurements as described by Rose and Weaver [4]. The third, and most accurate, is to fabricate a bipolar transistor and measure the base current.

The main drawback, common to all these methods, is that they require an ohmic contact to the emitter being studied. Consequently, they are incapable of measuring the properties of passivated emitter regions, even though such emitters are of great interest in the design of solar cells. In addition, any method suffers from the problem of separating the recombination in the emitter from the total recombination. We describe a measurement method which circumvents these limitations.

PRINCIPLE OF THE MEASUREMENT

The key features of the technique are the following: first, the carrier concentration in the sample is optically injected and subsequently monitored by a method of inductive coupling. This eliminates the need for an ohmic contact. Second, by putting the base into high-level injection, the emitter recombination has a quadratic dependence on the carrier density and is therefore separable from the linear recombination in the base and at the surfaces. Finally, emitter recombination is isolated by minimizing other sources of recombination. This is done by using lightly-doped, high-lifetime silicon for the base and a thermal oxide for passivation. The details of the measurement are described below.

The emitter of interest is placed on one side of a high-resistivity wafer of thickness, W, having a high-level injection lifetime, τ_{hli}. The other side is passivated with a high-quality thermal oxide, characterized by a surface recombination velocity, s. (Fig. 1) Again, no contact to the emitter is necessary. A flash lamp having a short pulse-width generates enough carriers to put the base into high-level injection, and the sheet photoconductivity σ_l is measured versus time by a contactless method which uses the principle of inductive coupling.[5] (Fig. 2) The measured quantity is proportional to σ_l, which is given by

$$\sigma_l = \int_0^W qn(\mu_n + \mu_p)dx \equiv q\overline{n}(\mu_n + \mu_p)W \qquad (1)$$

where $\overline{n}$ is the average photo-excited carrier density in the sample. (Equilibrium concentrations are nulled out by the circuit) The constant of proportionality is found by calibrating the detection circuit with wafers of known conductivity. The decay of σ_l depends on J_{0E}, τ_{hli}, s, and D_{amb} in a manner prescribed by the equations in the next section.

0160-8371/85/0000-0578 $1.00 © 1985 IEEE

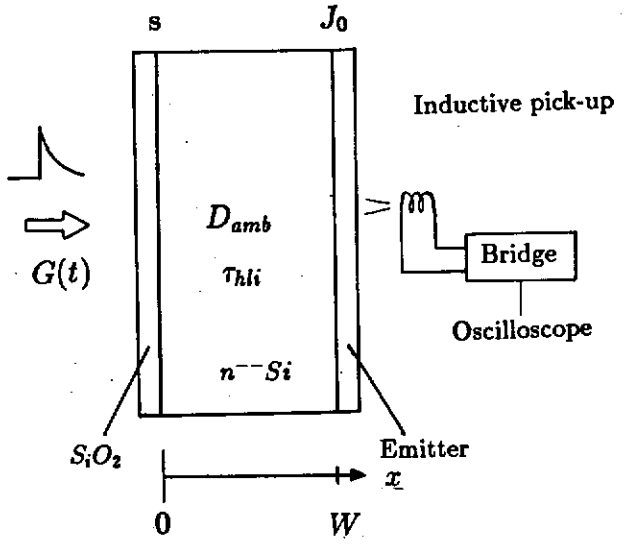

Fig. 1. - The experimental configuration. Carriers are generated optically by means of a flash lamp. The photoconductivity decay is monitored inductively.

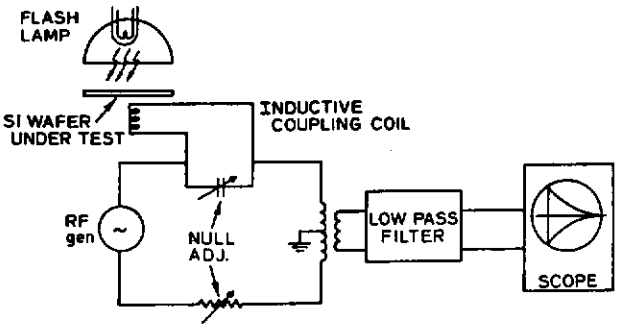

Fig. 2. - The photoconductivity measuring circuit. The steady-state conductivity is nulled out by the bridge.

THEORY

In the lightly-doped base, the standard high-level injection semiconductor equations apply. After generation has stopped,

$$\frac{dn}{dt} = -\frac{n}{\tau_{hli}} + D_{amb}\frac{d^2n}{dx^2} \tag{2}$$

At the passivated surface, $x = 0$,

$$J_n(0) = qsn(0) = qD_{amb}\frac{dn}{dx}\,|_{x=0} \tag{3}$$

At the emitter junction, on the base side of the space-charge region, $x = W^-$, the boundary condition is

$$-J_n(W^-) = J_{0E}\frac{p(W^-)n(W^-) - n_i^2}{n_i^2} = -qD_{amb}\frac{dn}{dx}\,|_{x=W^-} \tag{4}$$

Eq.(4) can be considered the definition of J_{0E} and is a valid description of an emitter in quasi-steady state provided a few non-restrictive assumptions apply [6]. These are 1) the material constants in the highly doped regions are independent of the minority carrier density, 2) the quasi-fermi levels are constant across the space-charge region, and 3) space-charge region recombination is negligible. Because the base is highly injected, $p = n \gg n_i^2$ and Eq.(4) becomes,

$$-J_n(W^-) = J_{0E}\frac{n(W^-)^2}{n_i^2} \tag{5}$$

In general, this non-linear boundary condition at the emitter junction makes an analytic solution to the above equations impossible. A related problem was treated by Schlang and Gerlach [7,8] and we have done a numerical simulation of the problem. The important result of this work is that when the diffusion length ($\sqrt{D_{amb}\tau_{hli}}$) is much longer than the base width and the diffusion velocity (D_{amb}/W) is much greater than the effective recombination velocity at $x = 0$ and $x = W^-$ (s or $J_{0E}n(W)/qn_i^2$ accordingly), the carrier density in the base rapidly becomes uniform after a few transit times, given by $W^2/2D_{amb}$. Since the excess carrier concentration in the emitter is everywhere less than that in the base, and the emitter is much narrower than the base anyway, the emitter contributes a negligible amount to the photoconductivity. In that case, $n(0) = n(W^-) = \overline{n}$, the measured quantity. Then, the total recombination is given by

$$J_{rec,total} = -qW\frac{d\overline{n}}{dt} = qW\frac{\overline{n}}{\tau_{hli}} + q\overline{n}s + J_{0E}\frac{\overline{n}^2}{n_i^2} \tag{6}$$

The solution to Eq. (6) is given by

$$\overline{n}(t) = \frac{\overline{n}(0)e^{-t/\tau_{eff}}}{1 + c(1 - e^{-t/\tau_{eff}})} \tag{7}$$

where

$$c = \frac{J_{0E}\tau_{eff}\overline{n}(0)}{qWn_i^2} \tag{8}$$

and

$$\frac{1}{\tau_{eff}} = \frac{1}{\tau_{hli}} + \frac{s}{W} \tag{9}$$

(Fig. 3). $t = 0$ is taken as that time when the carrier distribution first becomes uniform. The expression (7) reduces to a simple exponential if $J_{0E} = 0$, and to $1/t$ if J_{0E} dominates.

A conceptually easy way of extracting J_{0E} from an experimental decay is to plot $1/\tau_{inst}$, the reciprocal instantaneous decay time, versus $\overline{n}$

$$\frac{1}{\tau_{inst}} \equiv -\frac{1}{\overline{n}}\frac{d\overline{n}}{dt} = \frac{1}{\tau_{hli}} + \frac{s}{W} + \frac{J_{0E}\overline{n}}{qWn_i^2} \tag{10}$$

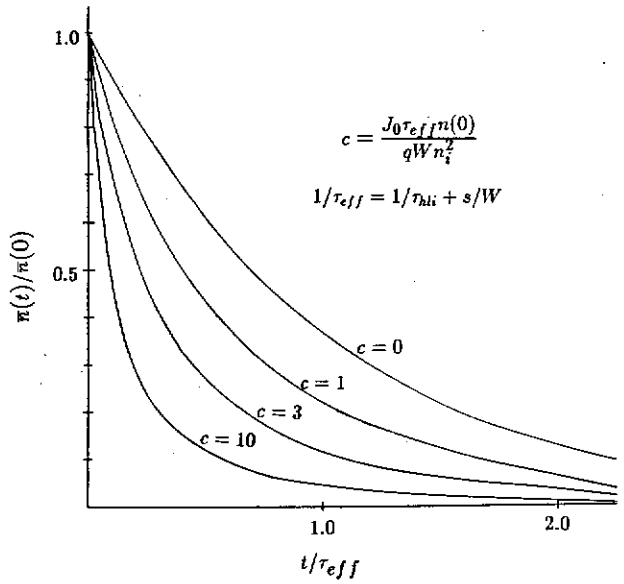

Fig. 3. - A theoretical photoconductivity decay curve. The parameter c measures the relative strength of the emitter recombination and the linear recombination.

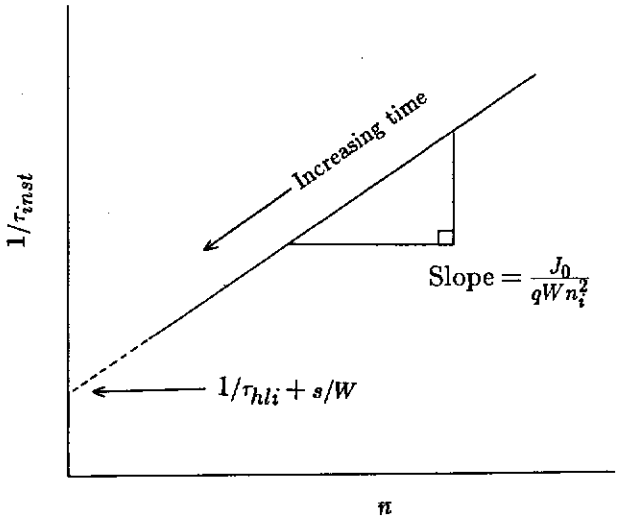

Fig. 4. - A simple extraction method. Each point on the line corresponds to a different time on the decay of Fig. 3.

The slope of the resulting line can be related to J_{0E} through known quantities.(Fig. 4) Thus, because the base is high-level injected, the recombination in the emitter can be separated from that in the bulk even when they are of comparable magnitude.

An additional feature of the measurement is that the measured quantity, J_{0E}/n_i^2, is relatively insensitive to temperature, in contrast to J_{0E} itself. This means that the measurement does not require precise temperature control.

LIMITATIONS OF THE METHOD

The theory suggests a promising technique for obtaining J_{0E}. Here, we will discuss some of its theoretical and experimental limitations.

From a theoretical point of view, the main limit to the extraction of J_{0E} arises from the fact that the mobility is finite, so that the carrier concentration cannot be strictly uniform for any non-zero recombination current in the emitter.

We can analyze the worst case of non-uniform carrier concentration by considering the case $s = 0$, $\tau_{hli} = \infty$, and $J_{0,E} \neq 0$. (This is the worst case because all the recombination occurs at one place and tends to set up a non-uniform distribution) Since the carrier density at the emitter junction is always lower than the average carrier density, the method underestimates J_{0E}. Fig 5. shows a plot demonstrating the effect of the assumption that the carrier concentration is uniform. When this assumption is relaxed, (solid line) we see that the decay rate increases

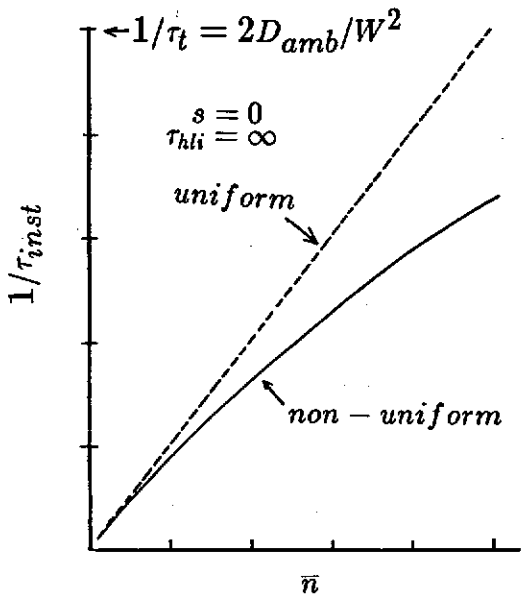

Fig. 5. - Assessment of the error involved in assuming a flat profile. The dashed line follows from the simple theory; the solid line from numerical modelling. Significant deviation occurs when the decay time approaches the transit time.

less rapidly as the recombination begins to be limited by the rate at which carriers diffuse through the sample. However, the error in J_{0E} is less than 10% as long as the decay time is greater than 6 times the transit time, $W^2/2D_{amb}$. Furthermore, if the diffusion constant is known reliably, these effects can be accounted for in the data extraction of J_{0E}. The problem can also be minimized experimentally by decreasing the base width.

For a cell of finite thickness, this effect puts an upper limit on the value of J_{0E} which can be measured. If the background doping is N_D, then the minimum carrier concentration for which the assumption of high-level injection remains valid is

$$n_{min} \approx 10N_D$$

The constraint on J_{0E} is then that the decay rate at this injection level is less than one-tenth of the transit time, or

$$J_{0E} < 0.1 \times q \times \frac{n_i^2}{n_{min}} \times \frac{D_{amb}}{W}$$

which gives a maximum J_{0E} of $10^{-11}A/cm^2$ for a wafer thickness of $100\mu m$ and a background doping of $5\times10^{13}cm^{-3}$. Of course, there may be additional practical limitations more restrictive than this. For example, n_{min} may be considerably greater than $10N_D$ due to the resolution of the detection circuit, or the decay rate might be so fast that it is comparable in length to the optical pulse width. For our apparatus, we estimate the upper limit to be $\approx 5 \times 10^{-12}A/cm^2$.

The other main limit to the extraction of J_{0E} deals with the validity of Eqs. 2 ,3, and 4. The analysis has assumed that τ_{hli} and s are independent of the carrier concentration. For SRH trap-mediated recombination, this is indeed the case in high-level injection. For Auger processes, however, the recombination is proportional to n^3. This begins to play a role in the bulk at a carrier concentration of approximately 10^{17}cm^{-3}. Finally, the surface recombination may not be linear over many orders of magnitude of carrier density. Uncertainties of this type place a lower limit on the measureable J_{0E}, estimated to be about $10^{-14}A/cm^2$ for our system.

The other source of error is in the calibration of the absolute carrier density from the photoconductivity. At an injection-level of 10^{17}cm^{-3}, the uncertainty in the mobility may be of the order of 20%. This translates directly to a like error in J_{0E}.

EXPERIMENT

A schematic of the experimental apparatus is shown in Fig. 2. The wafer is placed in close proximity to a two turn coil having a diameter of 1 cm. The generator frequency is 11 Mhz and the linearity of the circuit has been experimentally verified for all conductivities of interest. To convert the conductivity to carrier concentration, we use the mobility data of Dannhauser and Krause [10,11], and operate at densities where the uncertainty in the mobility is small.

High lifetime 100-200 Ω-cm n-type < 100 > float zone silicon was etched to the desired thickness. Doped glass was deposited on one side of the wafer, and the dopant was diffused into the Si at temperatures between $900 - 1120°C$. The glass was removed, and a high quality thermal oxide was grown at $1000°C$ for 90 minutes. After the J_{0E} measurement was performed on the passivated emitter, the passivating oxide was replaced by a thin layer of Al, and the J_{0E} measurement was repeated.

A typical experimental result is shown in Fig. 6. The decay conforms to the theory over a wide range of carrier concentration. The extracted effective lifetime, given by $1/\tau_{eff} = 1/\tau_{hli} + s/W$, is over 2 msec. This value is typical for our process. From other measurements, the best estimate of these parameters is $\tau_{hli} > 2$ msec and $s < 12$ cm/sec.[12,13]. They are clearly unimportant in the extraction of J_{0E}.

We have verified that identical results are obtained whether the initial illumination is through the oxide or through the diffused side. This indicates that asymptotic decay is independent of the initial excitation. This occurs when the sample width is less than the diffusion length.

As a test of the method, identical phosphorous emitters were formed on both sides of wafers of varying thicknesses. By putting the emitter on both sides instead of just one, the effective J_{0E} is doubled and the s/W term in (10) is not present. By eliminating surface recombination, it ensures that the emitter recombination is a greater fraction of the total. This is also a good idea if one suspects non-linear recombination at the oxidized surface. Fig.7 shows the results and the agreement with theory. Since the slope scales inversely with sample width, the increase in the recom-

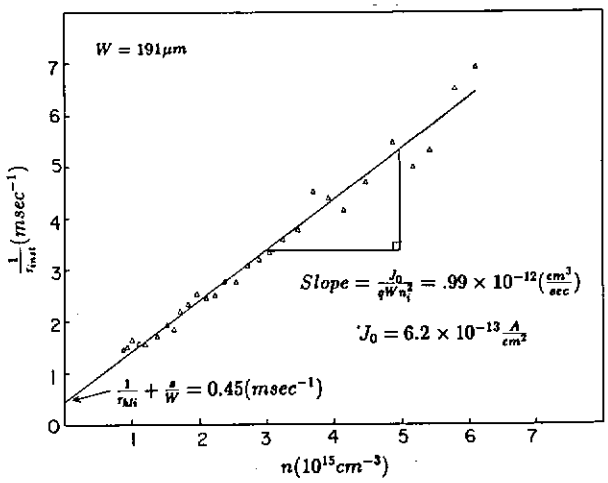

Fig. 6. - Typical experimental plot. The reciprocal decay time vs. injection level.

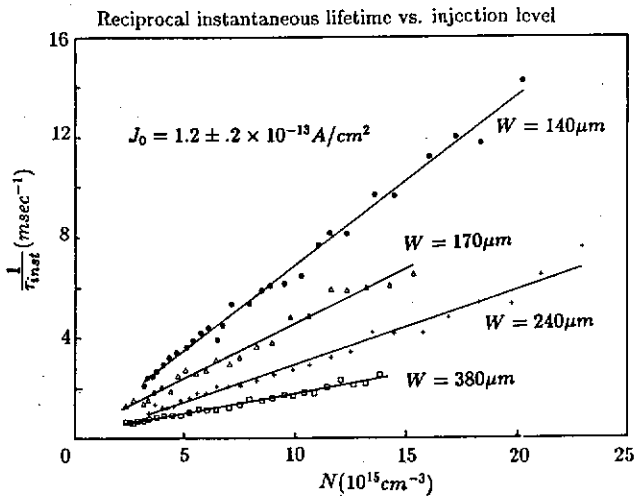

Fig. 7. - Test of the method. The extraction is carried out on wafers of different thickness having the same emitters.

bination rate at higher injection levels can be attributed unambiguously to emitter recombination.

With the foundations of the technique established, the measurement was performed on a variety of phosphorous and boron emitters having sheet resistances and surface concentrations varying over more than 2 decades.

Table 1 shows the results of measurements on phosphorous emitters. A complete analysis of the results requires a detailed emitter model [13] and is beyond the scope of this work. It is nonetheless instructive to note the trends which are apparent when the samples are arranged in order of increasing sheet resistance.

Comparing the J_{0E} of the metallized emitter to the J_{0E} of the passivated emitter shows how effective passivation can be. For the lightly doped emitters, the J_{0E} changes by over 2 orders of magnitude. This suggests an emitter which is relatively transparent to minority carriers and an emitter passivation which significantly reduces the recombination velocity. In contrast, the more heavily-doped emitters are insensitive to the surface treatment: this indicates an emitter dominated by Auger recombination in the heavily doped layer.

It is noteworthy that the requirements for a low J_{0E} emitter under a metal layer are very different from the requirements for a low J_{0E} emitter under a passivating oxide.

Table 2 shows the similar results for a set of boron diffusions. In general, boron emitters are not as well characterized as phosphorous emitters. Again, passivation has an effect on the J_{0E} of an emitter. It is not, however, as dramatic as that observed in phosphorous. This suggests that the surface recombination velocity is higher for electrons than holes.

Phosphorous emitters
Substrate: $N \approx 10^{13}$ cm^{-3}

$R_{sh}(\frac{\Omega}{\square})$	$x_j(\mu m)$	$N_{surf}(cm^{-3})$	$J_{0,pass}(\frac{fA}{cm^2})$	$J_{0,Al}(\frac{fA}{cm^2})$
9.0	5.8	5.0×10^{19}	0.45	0.50
57.2	3.6	1.2×10^{19}	0.10	1.10
75.3	1.8	2.0×10^{19}	0.13	1.70
370	1.2	2.5×10^{18}	0.08	1.70
890	1.3	1.0×10^{18}	0.01	7.00

Table 1 - Phosphorous emitters.

Boron emitters
Substrate: $N \approx 10^{13}$ cm^{-3}

$R_{sh}(\frac{\Omega}{\square})$	$x_j(\mu m)$	$N_{surf}(cm^{-3})$	$J_{0,pass}(\frac{fA}{cm^2})$	$J_{0,Al}(\frac{fA}{cm^2})$
5.3	4.8	7.0×10^{19}	0.35	0.42
37	2.1	3.6×10^{19}	0.07	0.57
63	3.0	1.3×10^{19}	0.09	1.10
240	1.1	5.4×10^{18}	0.13	1.00
463	1.2	1.3×10^{18}	0.06	1.10

Table 2 - Boron emitters.

SUMMARY

In conclusion, a straightforward measurement of the emitter saturation current is described and demonstrated. Since no ohmic contact is required,it is suitable for studying passivation techniques. It promises to aid in the optimization of solar cell emitter regions and to provide insight into the physical mechanisms taking place within the emitter.

Acknowledgments

This work was supported by EPRI contract RP-790-2. One of the authors (DK) was supported by a National Science Foundation graduate fellowship.

REFERENCES

1. R. M. Swanson,"Point-Contact Solar Cells: Modeling and Experiment", Solar Cells, to be published.
2. Y. Kwark, R. A. Sinton, and R. M. Swanson, These Proceedings.
3. M. A. Green, A.W.Blakers, Shi Jiqun, E.M.Keller, and S.R.Wenham, Appl. Phys. Lett. 44, 1163 (1984).
4. B. H. Rose and H. T. Weaver, "Method for determining emitter recombination in Si solar cells using open-circuit voltage decay", Appl. Phys. Lett. 45(3), August 1984.
5. H. Curtis and R. Verkuil, "A High Signal-to-Noise Oscillator for Contactless Measurement of Photoinduced Carrier Lifetimes", Lifetime Factors in Silicon, 1980, pp210-224.
6. J. Fossum and M. Shibib, "An Analytic Model for Minority-Carrier Transport in Heavily Doped Regions of Silicon Devices", IEEE Trans. on Electron Dev., ED-28, 1018, September 1981.
7. H. Schlangenotto and W. Gerlach, "On the post-injection voltage decay of p-s-n rectifiers at high injection levels", Solid-State Electronics, 15, pp393-402, 1972.
8. H. Schlangenotto and W. Gerlach, "On the effective carrier lifetime in p-s-n rectifiers at high injection levels", Solid-State Electronics, 12, pp267-275, 1969.
9. F. Dannhauser, Solid-State Electronics, 15, pp1371-1375, 1972.
10. J. Krausse, Solid-State Electronics, 15, pp1377-1381, 1972.
11. W. Eades and R. Swanson, "Calculation of the Surface Generation and Recombination Velocities at the $Si-SiO_2$ Interface", J. Appl. Phys., 15, Nov. 1985.
12. R. Sinton et. al., These Proceedings.
13. J. delAlamo and R. Swanson,"The Physics and Modeling of Heavily Doped Emitters", IEEE Trans. on Elec. Dev., ED-31, p1878, December, 1984.