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MINORITY-CARRIER DIFFUSION LENGTH: MEASUREMENTS BY EBIC, CONNECTION TO MATERIALS MICROSTRUCTURE AND RELATION TO DEVICE PERFORMANCE

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Abstract - The existing EBIC techniques for diffusion-length (DL) determination are reviewed and a new technique using a wedge-shaped absorber is introduced. The reliability of DL data is tested by comparing different methods. Connections between DL and silicon microstructure (crystal defects, levels in the forbidden gap, impurities) are discussed. Finally, effects of DL on device behaviour (junction leakage, latch-up) are sketched.

Résumé - Les méthodes de détermination de longueur de diffusion (DL) par la technique EBIC sont passées en revue et une nouvelle méthode utilisant un absorbant en forme de coin est introduite. La fiabilité des mesures de longueur de diffusion est testée par comparaison avec différentes méthodes. La correlation entre les valeurs de longueur de diffusion et la microstructure d'échantillon de silicium (défauts cristallins, niveaux d'énergie dans la bande interdite, impuretés) est discutée. Enfin, les effets de la longueur de diffusion sur le comportement du dispositif (fuite de jonction, auto-déclanchement) sont esquissés.

1 - INTRODUCTION

The minority-carrier diffusion length (DL), \( L \), is an important semiconductor parameter related to the recombination lifetime \( \tau_R \) by

\[
L^2 = D \tau_R
\]

with \( D \) being the minority-carrier diffusivity /1/. In silicon of low and medium doping levels, \( \tau_R \) is strongly influenced by recombination centres lying deep in the forbidden gap. These centres may be due to point defects (like heavy metal impurities) and/or extended crystal defects. The recombination lifetime resulting due to the presence of different recombination centres is

\[
\tau_R^{-1} = \sum_i \left( N_{T_i} \sigma_i \nu_{th} \right)
\]

with \( N_{T_i} \) being the concentration of the \( i \)-th centre, \( \sigma_i \) its capture cross-section for minority carriers and \( \nu_{th} \) the thermal velocity of minority carriers. Fig. 1 shows lifetime and diffusion length of electrons in p-type silicon as a function of \( N_T \) with \( \sigma \) as parameter.

In as-grown silicon typical DL values are in the range of 100 \( \mu \)m or larger /2/. During processing, however, the DL may decrease down to a few \( \mu \)m as a result of contamination by impurities and formation of crystal defects (see Fig. 2). For the usual doping levels of silicon substrates in the range \( 10^{14} \ldots 10^{16} \) \( \text{cm}^{-3} \), recombination via recombination centres is the main recombination path and the doping concentration \( N_D \) has nearly no influence on recombination.
Fig. 1 - Lifetime $\tau_R$ and diffusion length $L_e$ of electrons in p-type silicon in dependence on the concentration of recombination centres $N_T$ and with capture cross-section $\sigma_n$ as parameter (room temperature, curves calculated from (2) and (1)).

Fig. 2 - Diffusion length $L$ versus annealing temperature: PZ silicon, diffusion-length measurements by PEM (Dr. E. Susi, IABM, Bologna) and EBIC.

At higher doping, however, $\tau_R$ and $L$ become dependent on $N_D$ because of increasing importance of Auger recombination. Besides recombination lifetime $\tau_R$ there is another lifetime often found in the literature, the so called generation lifetime $\tau_G$. The generation lifetime, determined by thermal emission processes, characterizes regions depleted from charge carriers. Under certain conditions the relation between $\tau_G$ and $\tau_R$ may be written /3/

$$\tau_G \propto 2 \tau_R \sqrt{\frac{\sigma_n}{\sigma_p}} \cosh\left[\frac{(E_T-E_i)/kT}{(E_T-E_i)/kT}\right]$$

with $\sigma_n(\sigma_p)$ as capture cross-section for electrons (holes), $E_T$ as the energy level of the recombination/generation centre, $E_i$ as the intrinsic level and $k$ as the Boltzmann constant. Due to the dependence on $(E_T-E_i)$, $\tau_G$ and $\tau_R$ may differ very largely with $\tau_G \gg \tau_R$. Nevertheless, the differences between recombination and generation lifetime are often overlooked, leading to misinterpretations then.

Both, $\tau_R$ and $\tau_G$, are important parameters and have regard to device performance. As to $\tau_R$ or $L$, they influence, e.g., junction leakage and refresh behaviour of memory devices (especially at elevated operation temperatures), current gain of bipolar transistors, switching behaviour, latch-up of CMOS devices, radiation hardness and efficiency of solar cells. Therefore, knowledge of $L$ resp. $\tau_R$ in small regions is of increasing interest.

There is a lot of methods for the investigation of recombination /1/, among them the well established methods of photoconductivity (PC), photo-electromagnetic effect (PEM), and surface photovoltage (SPV). Most of them are, however, methods averaging over a large volume, i.e. they have poor spatial resolution, and do not allow to observe inhomogeneities of recombination on a microscopic scale. High spatial resolution can be obtained only when focused beams are used for charge-carrier generation, as in the case of the EBIC method /4,5/.

The present paper reviews the different EBIC techniques used for DL determination and discusses connections of DL to materials microstructure and to possible impacts on electronic device behaviour.
2 - DIFFUSION LENGTH DETERMINATION BY EBIC

2.1 - STATIONARY MEASUREMENTS FOR HOMOGENEOUS MATERIAL

The following stationary EBIC techniques are commonly used for diffusion-length (DL) determination, see Fig. 3:

EBIC decay at junctions being perpendicular to the scanned surface (method 1), EBIC decay near shallow junctions or Schottky barriers respectively, being parallel to the scanned surface (method 2), EBIC decay at extended crystal defects, in particular grain boundaries (method 3) as well as measurements of the EBIC signal at directly irradiated junctions in dependence on the beam energy (method 4). There is a large number of papers dealing with this topic, so the references to the different methods given below are far from being complete.

2.1.1 - PHENOMENOLOGY

Method (1), see /6-8/, can be regarded as "classical" method of DL determination. When the electron beam is scanned across the sample the EBIC signal decreases with distance to the junction, x, thereby x = 0 being the position of the depletion-layer edge. Fig. 4 shows an example of DL measurements using this method.

Fig. 3 - Different EBIC methods for DL determination (schematic).

Fig. 4 - DL measurement using method (1): experimental data for 3 different beam energies (A, O, □) and corresponding theoretical curves. The theoretical curves fit well the experimental profiles when a diffusion length profile is assumed, with L = 32 μm near the surface and L = 40 μm for depths larger than 40 μm (measurements and analysis by Dr. F. Koch, Humboldt-Univ. Berlin).
The profile $I_{EBIC}(x)$ depends on $L$, but is also affected by surface recombination $S$ and beam energy $E_0$, respectively electron range $R$. For sufficiently large distances and $R \ll L$ there holds approximately:

$$I_{EBIC}(x) \propto \exp(-x/L) \quad \text{for} \quad S \rightarrow 0$$

and

$$I_{EBIC}(x) \propto \exp(-x/L)(x/L)^{-1/2} \quad \text{for} \quad S \rightarrow \infty /5/.$$

Method (2) is based on the analysis of similar decay curves, but obtained for surface-parallel collecting contacts. In contrast to method (1),

$$I_{EBIC}(x) \propto \exp(-x/L) x^{-n}$$

with $n = 3/2$ for $S \rightarrow \infty$ and $n = 1/2$ for $S \rightarrow 0$ is approximately true/9,16/.

Method (3), see /10/, uses a shallow collecting contact at the sample surface. The DL is determined from the profile of the EBIC signal $I_{EBIC}(x)$ near a recombination-active grain boundary lying perpendicular to the surface. In principle information about DL can be obtained from $I_{EBIC}(x)$ also in the case of other defect geometries.

Method (4) /11,12/ uses also surface-parallel collecting contacts and is based on measurements of the collection efficiency $\eta$ vs beam energy $E_0$. The efficiency is obtained from

$$\eta_{Si} \approx \frac{I_{EBIC}}{250 I_b E_0 (keV)^4}$$

The experimental $\eta(E_0)$ curve depends on $L$, but also on the other parameters characterizing the sample (e.g. dead layer thickness, depletion layer width). Fig. 5 shows modelled $\eta(E_0)$ curves and Fig. 6 a measured $\eta(E_0)$ curve.

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Fig. 5 - DL measurement using method (4): $\eta(E_0)$ curves calculated for a Schottky diode with metal thickness $m = 0.05 \mu m$ and depletion layer width $w = 0.25 \mu m$, diffusion length $L$ as parameter.

Fig. 6 - DL measurement using method (4): experimental data (o) and modelled $\eta(E_0)$ curve yielding $L \approx 6.5 \mu m$.

$+)$ $I_b$ ... beam current
The variation of $E_g$ is equivalent to a change of the distance between generation source and junction. So this technique can be also regarded as a spatial decay technique like methods (1) to (3).

Important characteristics of the 4 different methods are compared in Table 1.

Table 1 - Comparison of different EBIC techniques used for DL determination

<table>
<thead>
<tr>
<th>method to be measured</th>
<th>diffusion length range</th>
<th>spatial resolution</th>
<th>stability</th>
<th>time consumption</th>
<th>remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) position $x$</td>
<td>$L_{min}$ /21/</td>
<td></td>
<td>instabilities during irradiation</td>
<td>few</td>
<td>to define $x=0$</td>
</tr>
<tr>
<td>absolutely,</td>
<td>$L_{max}$ limited by sample dimensions</td>
<td></td>
<td>of the free surface possible</td>
<td>few minutes</td>
<td></td>
</tr>
<tr>
<td>(2) $I_{EBIC}$ relatively</td>
<td></td>
<td></td>
<td>no problems when using</td>
<td>high time</td>
<td>1:1 correlation of DL measurement and defect characterization</td>
</tr>
<tr>
<td>(3) $I_{EBIC}$, $I_b$, $I_{max}(Si)$</td>
<td>$\leq 50$ μm</td>
<td></td>
<td>good Schottky contacts</td>
<td>consumption</td>
<td></td>
</tr>
<tr>
<td>(4) $I_{EBIC}$, $I_b$, $I_{max}(Si)$</td>
<td></td>
<td></td>
<td></td>
<td>30 min</td>
<td></td>
</tr>
<tr>
<td>absolutely</td>
<td>(at $E_o$ 40 keV)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2.1.2 - ANALYSIS OF MEASURED DATA

Method (1)

A rough estimation of $L$ is rapidly obtained from the slope of the linear part of $\ln [I_{EBIC}(x)]$. The DL so determined is an effective DL $L_e$ with $L < L$ in general /13/. An accurate determination of $L$ is possible when modelled curves are fitted to experimental $I_{EBIC}(x)$ profiles measured at two or more different beam energies. Besides $L$ also the surface recombination velocity $S$ is obtained. Fig. 4 gives an example. As visible even inhomogeneities of $L$ can be measured in this way. The numerical effort for analysis is, however, quite large.

A less expensive method uses the moment /14/:

$$ m = I_{EBIC}(0)^{-1} \int_0^\infty x \cdot I_{EBIC}(x) \, dx \quad (7). $$

If $m$ is determined for 2 different beam energies $L$ and $S$ can be obtained. Another method of analysis is given in /15/. The positions $x_1$ and $x_2$ ($I_{EBIC}(x_1) / I_{EBIC}(0) = 10^{-1}$, $I_{EBIC}(x_2) / I_{EBIC}(0) = 10^{-2}$) are determined from $I_{EBIC}(x)$ and then used to obtain $L$ from a modelled diagram.

Of course the latter analysis methods don't allow to detect inhomogeneities of $L$ (demonstrated in Fig. 4) and yield, therefore, mean DL values.

Method (2)

If $S \rightarrow \infty$ is true for the free surface the DL is directly found from the slope of the linear part of $\ln \left[I_{EBIC}(x) \cdot x^{3/2}\right] /9/.

The DL can also be obtained from the moments of two $I_{EBIC}(x)$ profiles measured at different $E_0$. This method is not limited to $S \rightarrow \infty$, but works for arbitrary $S$. For details the reader is referred to /16/.

$$ \nabla \Sigma = S l / D $$
Method (3)

The following two parameters calculated from the $I_{EBIC}(x)$ profiles:

$$A = \int_{-\infty}^{\infty} i^*(x)dx, \quad S^2 = A^2 \int_{-\infty}^{\infty} x^2 i^*(x)dx$$

allow to obtain $L$ and $S$ using a special diagram /10/.

Method (4)

Theoretical $\eta(E_0)$ curves are fitted to a set of experimental $\eta(E_0)$ data (see Fig. 6) /17/. For a Schottky diode, fit parameters are $L$, metal layer thickness $m$, and depletion layer width $w$. The method can be used for p-n junctions, too. Then, of course, the number of fit parameters increases.

If $m$ and, in particular, $w$ are approximately known the DL can be estimated from only one value of $\eta$, measured at sufficiently large $E_0$. Calculated $\eta$-vs-$L$ curves as shown in Fig. 7 are used for this purpose /18/. Thereby, an $\eta$-measurement near 20 keV is recommended for checking the quality of the prepared Schottky contacts.

Fig. 7 - DL determination using method (4): $\eta$ vs $L$ calculated for a Schottky diode with $m = 0.1 \mu m$ and $w = 0.4 \mu m$ ($E_0 = 40$ keV).

Fig. 8 - Comparison of DL measured on the same samples by EBIC and PEM: PEM measurements without surface removal, EBIC measurement before (o) and after (c) surface removal.

A further simplified analysis method refers to the decrease of $\eta$ in the high-energy part of the $\eta(E_0)$ curves. In the high-energy region the semilogarithmic $\eta$-vs-$R$ curves for a given value of $L$, but different $w$, are identical in shape but shifted vertically over a distance $(w/L)/19/$.

It can be seen in Figs. 5 and 7 that $L$ variations cause smaller and smaller changes of $\eta$ with increasing DL. Therefore, for silicon the upper DL limit of this method is about 50 $\mu m$ at usual beam energies near $E_0 = 40$ keV /20/.

2.1.3 - COMPARISON OF DIFFUSION LENGTHS OBTAINED BY DIFFERENT METHODS

For some applications, see e.g. chapter 3, absolute DL values are required. However, absolute measurements of DL resp. lifetime are not seldom problematic. So, comparative measurements of $\tau_R$ in different laboratories were reported to yield lifetimes differing by up to a factor 100 /22/. To check the accuracy and reliability of the DL data measured the different EBIC methods (1) to (4) as well as method (4) and PEM are compared here.
A) Comparison of different EBIC techniques

Table 2 presents results of comparative DL measurements carried out using the EBIC methods (1) to (4).

Table 2 - Comparison of diffusion-lengths obtained by different EBIC methods

<table>
<thead>
<tr>
<th>DL determined by method (4)</th>
<th>DL determined by method(1a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 μm</td>
<td>32 μm (1a)</td>
</tr>
<tr>
<td>45 μm</td>
<td>50 μm</td>
</tr>
<tr>
<td>25 μm</td>
<td>26 μm</td>
</tr>
<tr>
<td>22 μm</td>
<td>23 μm</td>
</tr>
<tr>
<td>70...80 μm</td>
<td>90 μm (2b)</td>
</tr>
<tr>
<td>40 μm</td>
<td>40 μm (3)</td>
</tr>
</tbody>
</table>

a) investigation by Dr. F. Koch, see Fig. 4
b) investigation according to /16/ by Dr. C. Donolato

Good correspondence between the different methods is found showing that EBIC measurements yield reliable data.

Further comparative studies using methods (2) and (3) are reported in /23/.

B) Comparison between EeeC and PEM

Fig. 8 shows LEBIC vs PEM as measured for heat-treated p-type CZ silicon. The samples studied had a DL profile with lower DL values in the bulk than at the surface. The EeeC measurements were carried out by method (4) first at the surface (0) and then, after surface removal in the sample bulk (0). The PEM measurements were done before the EeeC investigations when the surface layer was not yet removed.

The EeeC data determined at the surface fall all near the line PEM/EBIC = 1 whereas for the EeeC data in the volume PEM/EBIC > 1 is observed. This indicates that the PEM measurements provided information not about the whole sample, but mainly about the surface-near part, similar to EeeC at the surface. The scatter of the surface data (0) around the line PEM/EBIC = 1 might be due to micro-inhomogeneities and/or measuring errors.

So, in contrast to a previous study /24/ a good correspondence between DL determined by EeeC and PEM is found.

Summarizing it can be stated that the presented results demonstrate the reliability and accuracy of the EeeC DL data.

2.1.4 - A NEW METHOD USING A WEDGE-SHAPED ABSORBER

The main disadvantage of method (4) - very high time consumption - can be overcome in the following way: Instead of changing the primary-beam energy, the "energy variation" necessary for DL determination is realized by inserting a wedge-shaped absorber (e.g. silicon) between primary beam and sample to be measured (Fig. 9). The effective energy E of the beam reaching the sample, and thus the depth of penetration into the sample decreases with increasing wedge thickness. Accordingly, the LEBIC-vs-wedge-position curve contains information about the sample properties, in particular about DL.

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*Patent pending*
Fig. 9 - Illustration of the new method of DL determination: the EBIC
signal is measured as a function of wedge position.

Fig. 10 - Modelled dependence of collection efficiency $\eta$ on wedge thick-
ness $t$ ($R = 10 \mu m$, Everhart-Hoff depth-dose function /28/ assumed).

Results of corresponding rough model calculations for a Schottky junction
are given in Fig. 10. The silicon wedge with its position-dependent thick-
ness $t$ was assumed to act simply as a dead layer on the sample. Further,
the Everhart-Hoff depth-dose function /28/ was used. For large and medium
DL, $\eta$ decreases monotonously with increasing wedge thickness whereas it
may reach a maximum before decreasing to zero for very small DL. The slope
of the $\eta$ curves near $t = 0$ is seen to have a pronounced dependence on $L$.

Experimental results for samples of different DL values are in qualitative
agreement with the curves of Fig.10 and demonstrate that the method
can well be used for DL determination.

However, the first measurements also show that the interaction of the pri-
mary beam with wedge and sample is not completely understood. Further ex-
perimental and theoretical studies are necessary to solve this problem.

As the method provides a continuous $\eta(t)$ curve, a depth profiling of the
collection probability $\varphi(z)$ proposed by Donolato /5/ seems to become
possible in future.

For more detailed information the reader is referred to /25/. The proposed
new method is realized technically by Raith KG, Dortmund, FRG.

2.2 - STATIONARY MEASUREMENTS FOR MATERIAL CONTAINING A DEPTH PROFILE

Intrinsic gettering processes, nowadays widely used in the Si technology
/26/, lead to the formation of distinct DL profiles in the wafers. These
profiles can be evaluated from $\eta(z)$ profiles measured on bevelled samples
for sufficiently large beam energy, typically $E_0 \sim 40$ kev.

Fig. 11 shows the corresponding measuring geometry with the Schottky con-
tact on the bevel and Fig. 12 presents obtained results.

The $\eta(z)$ profile measured can be converted into a DL profile using an
$\varphi(L)$ curve as given in Fig. 7. Because of the existing depth profile the
obtained DL values are not the true DL's at the respective depth, but some
effective DL $L^{*}(z) < L(z)$. The effective DL at the sample surface $L^{*}$ has
nevertheless direct practical meaning as it is related to the diffusion
component of the leakage current of junctions (see /18/ and chapter 4).

The "true" DL profile $L(z)$ can be found using /27/

\[
L(z_r) = \int_0^z f(r) \left[1 + f'(r)\right]^{-\frac{1}{2}} dr, \quad f(z) = -\frac{a}{\ln \eta(z)}
\]

\[(9)\]
It should be emphasized that \( L(z) \) determination requires preparation of high quality Schottky contacts on bevels. Because bevelling may lead to electrically active damaged layers (e.g., conversion of the conductivity type from p- to n-conductivity beneath the bevel plane /17,20/) preparation and checking the contact quality must be carried out carefully.

Fig. 11 - Charge collection microscopy at bevelled samples having DL depth profiles (schematic)

Fig. 12 - EBIC investigation of an intrinsically gettered sample: micrograph and profiles of collection efficiency \( \tau(z) \), effective DL \( L^* \) ( ), and true diffusion length DL \( L \) ( ). The micrograph is shown with the same depth scale as the profiles.

2.3 - PHASE-SHIFT MEASUREMENTS USING A MODULATED BEAM

Measurements with a modulated beam in geometry 1 and 2 (see Fig. 3) provide additional possibilities to characterize recombination properties. Due to the modulation a phase shift \( \Phi \) occurs between \( I_b \) and \( I_w \) which increases with scan distance \( x /29/ \). As the phase shift depends on the ratio of modulation period \( T = f^{-1} \) to lifetime \( \tau_R \), measurements of \( \Phi \) vs \( x \) at appropriate modulation frequencies \( f \) allow to investigate recombination properties. Thereby, it is of advantage that the \( \tau(x) \) profiles are practically not influenced by the value of the surface recombination velocity /29,30/.

If \( L \) is already known, \( \tau_R \) can be obtained from the experimental data \( d\Phi/dx \) using /29/:

\[
L \frac{d\Phi}{dx} = \frac{0.87}{\sqrt{12}} \frac{\omega \tau_R}{2 \Gamma} \left[ 2 + \frac{1}{\omega \tau_R} + 1 \right]^{1/3}
\]

with \( \omega = 2\pi f \).

Such phase shift measurements carried out on a p-type silicon sample (\( \rho < 1.3 \text{ ohm cm} \)) are shown in Fig. 13.
2.4 - MEASUREMENTS IN THIN LAYERS

Thin semiconductor layers are increasingly used in electronic device production (e.g. CMOS, SOI). The characterization of recombination in such layers with thicknesses $d < L$ is problematic, because recombination at the interfaces bounding the layer is often dominating and leads to effective DL values $L_{\text{eff}} \ll d$, see e.g. /13/. Determination of the real bulk DL of the layer is possible only when measures are taken to avoid recombination of minority carriers at the interfaces. This can be realized by electrical barriers repulsing minority carriers, e.g. by high-low junctions or MOS capacitors biased into accumulation.

Fig. 13 - Lifetime determination by phase shift measurements: experimental arrangement and results, see /31/.

Decay measurement of $I_{\text{EBIC}}(x)$ yielded $L \approx 70 \mu$m so that a lifetime $\tau_R = 4 \mu$s was found from the measured phase gradient $\frac{d\psi}{dx}$. Accordingly, an electron diffusivity $D_n \approx 12$ cm$^2$/s was calculated from $D = L^2/\tau_R$, a value much smaller than the normally reported diffusivities for electrons as majority carriers. Although similar results with $D_{\text{minor}} < D_{\text{major}}$ can be found in several papers /29, 32-34/, there is not convincing explanation so far. Further investigations are needed to check this question.

Fig. 14 - Sample structure for DL measurements in thin layers /35/. Instead of the MOS capacitor also a high-low junction may be used to realize a low surface recombination.

Fig. 15 - Plot of experimental data as $\ln[I_{\text{EBIC}}(x) \cdot x^{0.5}]$ vs $x$. 
Fig. 14 shows the geometry of a sample used for determination of the layer DL by the lateral decay method. This type of geometry has been proposed in /35/ for EBIC measurements. The p-type epitaxial layer to be characterized was about 1.5 \( \mu m \) thick and was located on a p\(^+\) buried layer. The free surface near the shallow p-n\(^+\) diode used for charge collection had a shallow p\(^+\) implant to avoid surface recombination. The DL obtained from the decay of the \( \ln [I_{\text{EBIC}}(x)] \) vs \( x \) curve are in the range of 25 . . . 30 \( \mu m \). However, the curve was not linear as would be expected for zero recombination velocity, thus indicating that there is still some influence of the interfaces. A quite linear curve is found if \( \ln [I_{\text{EBIC}}(x) \cdot 10^{-5}] \) is plotted against \( x \), yielding \( L \approx 50 \mu m \) (Fig. 15). Although the data analysis was not based on theoretical models and the DL values shall be considered as rough estimates, only these results demonstrate without doubt that the geometry shown in Fig. 14 allows to measure DL values \( L > d \) by using EBIC.

3 - CONNECTION OF DIFFUSION LENGTH WITH MATERIALS MICROSTRUCTURE

In this chapter we discuss connections of DL with material structure and illustrate by examples what kind of additional information can be deduced from DL measurements.

3.1 - DETERMINATION OF THE CONTENT OF INTERSTITIAL IRON IN BORON-DOPED SILICON

In boron-doped silicon iron is known to form Fe\(_i\)B\(_i\) pairs with an energy level at \( E_g + 0.1 \) eV /36/. These pairs can be destroyed (e.g. by forward biasing the Al Schottky diode used in EBIC investigations) thus leading to the appearance of the interstitial iron Fe\(_i\) with a level at \( E_g + 0.4 \) eV.

As the Fe\(_i\)B\(_i\) pairs do not influence recombination while interstitial iron is an efficient recombination centre DL measurements before and after Fe\(_i\)B\(_i\)-pair destruction can be used to estimate the interstitial iron concentration[Fe\(_i\)] under favourable conditions /37/. Namely, if \( I_d \) is the DL before pair destruction (\( I_d \) determined by recombination via centres other than iron) and \( I_d \) is the DL after pair destruction (\( I_d < I_d \) because of the additional recombinaton path via Fe\(_i\)) one may calculate [Fe\(_i\)] from the formula

\[
[\text{Fe}_i] = \left( L_d^2 - L_u^2 \right) \frac{D_n}{\varepsilon_n(\text{Fe}) V_{th}}
\]

with \( \varepsilon_n(\text{Fe}) = 2 \times 10^{-14} \text{ cm}^2 /38/ \). The obtained interstitial iron concentrations were found to be in good agreement with DIFS data /37/.

[Fe\(_i\)] depth profiles can also be obtained if the corresponding diffusio-length profiles \( I_d(z) \) and \( I_d(z) \) are determined by the method given in chapter 2.2 – see Fig. 16.

3.2 DETERMINATION OF THE ENERGY LEVELS OF CENTRES BY \( L(T) \)

Measurements of the temperature dependence of lifetime or DL provide the possibility to determine the energy position of centres responsible for recombination.

Such kind of investigations were carried out by method (4) on a polycrystalline solar cell with a shallow p-n junction. The temperature dependence of the DL, \( L(T) \), was obtained from the temperature dependence of the collection efficiency, \( \eta(T) /39/ \). To get the lifetime \( \tau(T) \),

\[ D_n \propto T^{-0.5} \] was assumed for the electron diffusivity, giving \( \tau(T) \propto L^2(T) \cdot T^{-0.5} \).

The experimental data shown in Fig. 17 were measured in a sample area which seemed to be defect-free at \( T = 300 \) K, but had a high density of dark point-like EBIC contrast at low \( T /39/ \). The observed temperature dependence of \( \tau \) can be described by the Shockley-Read-Hall recombination theory, if a level at \( E_g + E_p = 0.07 \) eV or \( E_p = E_C - 0.07 \) eV is assumed (full curve in Fig. 17). The result shows that \( L(T) \) measurements may be of interest for the characterization of local electrical properties.
3.3 - CONTRIBUTION OF DENSELY NEIGHBOURED EBIC DEFECT CONTRASTS TO THE AVERAGE DL

For intrinsic gettering and lifetime engineering knowledge about the sources of volume recombination is important because only with this knowledge device properties can be controlled in a definite manner (compare chapter 4). The bulk of intrinsically getterted (IG) silicon is characterized by a high density of defects which lead to closely neighboured dark EBIC contrasts, compare Fig. 12.

It is obvious that such crystal defects showing dark EBIC contrasts reduce the average diffusion length in the material because dark contrasts indicate additional recombination. However, crystal defects having EBIC contrast are not the only causes of bulk recombination. Other crystal defects not resolvable by EBIC due to their low recombination activity and/or their high density and point defects may also contribute to bulk recombination (Fig. 18). So, to a first approximation the resulting average diffusion length in the bulk of the sample, \( L_B \), is given by:

\[
L_B^2 = L_E^2 + L_M^2
\]  

(12),

with \( L_E \) describing the contribution of the observed defects with EBIC contrasts and \( L_M \) the contribution of the surrounding material being due to point defects and crystal defects without contrast (recombination background).

\( L_E \) can be determined directly by energy-dependent charge collection measurements \( \eta (E_0) \) \(^{17/} \), while \( L_M \) could be estimated from contrast data \(^{40,42/} \):

\[
L_E \approx \lambda \left( \frac{R_{f_{\text{max}}}}{C_{\text{max}}} \right)^{1/2}
\]  

(13).
Fig. 18 - Volume defects in annealed Cz silicon.

a) EBIC micrograph of an annealed p-type silicon sample \( (E_0 = 30 \text{ keV}) \)
b) Schematic illustration of the different defect types contained in a sample: Defects having EBIC contrast (full circles) define the DL component \( L_0 \) while point defects (points) and extended defects giving no EBIC contrast (open circles) determine the component \( L_m \).

\( \lambda \) is the average distance between EBIC contrasts, \( c_{\text{max}} \) the maximum EBIC contrast in the sample area investigated, \( R \) the electron range /28/ at the beam energy \( E_0 \) used for imaging and \( f_{\text{max}} \) a correction factor to be calculated - for more detailed information on \( c \) and \( f \) see below.

Application of relation (13) to experimental data proved to yield quite satisfactory results, e.g. \( L_E > L_0 \) in all cases as required by (12) /42/.

Relation (13) is briefly explained below. The contrast \( c \) of an isolated point-like defect with recombination strength \( \gamma \) is given by

\[
C = \gamma \cdot f_{d}(a; L_M, R)
\]  

(14).

Fig. 19 - EBIC contrast of point-like defects.

a) Correction factor \( f_{d} \) versus defect depth \( a \), calculated for \( R = 6 \mu\text{m} \) and different diffusion lengths \( L_m \).
b) Contrast \( c \) versus defect depth \( a \), with defect strength \( \gamma \) as parameter. \( \gamma_{\text{max}} \) is the maximum \( \gamma \) found in the sample, \( \gamma_{\text{min}} \) the minimum \( \gamma \) still able to produce visible contrast, and \( \gamma(a') \) is an intermediate value which produces a contrast \( c_{\text{min}} \) at a depth \( a' \). \( a_u \) and \( a_l \) define the depth range where contrast may be observed.
\( f_d \) is the correction factor with the electron probe above the defect and can be calculated after /41/ (see Fig. 19a). It can be shown that the contrast \( c^* \) of a defect surrounded by other defects is nearly equal to the contrast of an isolated defect with the same parameters, provided \( \chi \) is not too large and \( \chi > 2r \) holds for the defect distance. Thus, relation (14) can be used for densely defect accumulations, too. \( \chi \) of a defect and, consequently, also the defect contrast are related to number and capture cross-section of recombination centres located at the defect. To estimate \( L_E \) all these defect recombination centres were treated as being distributed homogeneously in the depth interval \( \Delta a = a_1 - a_2 \) in which contrasts may be observed. Fig. 19b sketches the situation. Only features with \( c > c_{\text{min}} \) are detected and can be taken into account when calculating \( L_E \).

Assuming a homogeneous distribution of \( \chi \) up to a certain maximum strength \( \chi_{\text{max}} \) and a homogeneous defect depth-distribution, an expression of the following type is obtained /40/:

\[
L_E = \lambda \left( \frac{R f_{\text{max}}}{c_{\text{max}}} \right)^{1/2} F \left[ c_{\text{max}}, c_{\text{min}}, f(a, \ldots) \right]
\]

(15).

The function \( F \) is near 1 for \( 0.1 < c_{\text{min}}/c_{\text{max}} < 0.9 \). This means that relation (13) can well be used to estimate \( L_E \) under normal contrast conditions.

Fig. 20 shows \( L_E \) -vs- \( \lambda \) curves calculated from (12) and (13) and experimental data measured (+) in the bulk of intrinsically gettered silicon samples of p-type conductivity. \( L_E \) was measured using method (4) and \( \lambda \) was determined at \( E_0 = 30 \) keV.

A detailed analysis from the available data was carried out for 2 samples in the lower and upper part of the \( L_E \)-vs- \( \lambda \) diagram (samples A and B) /40, 42/. This analysis leads to the conclusion, that stacking faults control \( L_E \) and represent essential sources of recombination in intrinsically gettered p-type silicon. Oxygen precipitates which codetermine the recombination background \( L_M \) are not dominant in the samples investigated, in contrast to /43/.

![Graph showing \( L_E \) vs. \( \lambda \)]
The role of recombination properties in device operation was already emphasized in the introduction. Now, junction leakage and latch-up immunity will be discussed briefly.

The leakage current density $J_L$ of a junction consists of different components and may be written /44/:\[ J_L = \frac{q n_i w}{t_D} + \frac{q n_i^2 D}{N L} + \ldots \] (16).

The first term describes the generation component from the space charge layer and the second term is the diffusion-current density $J_D$ from the neutral semiconductor surrounding the junction. Further terms are possible but are omitted here. $J_D$ depends on the DL and is often the dominating component in the total leakage at elevated operation temperatures, e.g. $T \approx 80$ °C. Accordingly, $J_L \propto J_D$ holds then.

For material with DL profiles like after intrinsic gettering

$$J_D \approx \frac{q n_i^2 D}{N} \frac{1}{L^*_S}$$

(17)

is valid /16/. That means that $J_D$ can be estimated from the effective DL at the surface $L^*_S$ (compare chapter 2.2), without need to determine the whole $L(z)$ profile.

For low leakage currents $J_L$ at operation temperature $L^*_S$ values as high as possible are required. Typically, $L^*_S$ is around 10 µm for intrinsically gettered silicon of p-type conductivity.

![Fig. 21 - Schematic cross-section of a CMOS structure, with the parasitic lateral (2) and vertical (3) bipolar transistors and the parasitic p-n-p-n structure (1) indicated. $L_{DZ}$ and $L_B$ are the diffusion lengths in the denuded zone and in the bulk, and $w_{DZ}$ is the width of the denuded zone.](image)

Also latch-up behaviour of CMOS circuits is influenced by DL. Such circuits contain parasitic vertical (3) and lateral (2) bipolar transistors which form a parasitic lateral p-n-p-n structure (1) – see Fig. 21. One way to avoid regenerative switching (latch-up) of this parasitic structure is keeping the product of the current gains of the parasitic transistors less than 1. It seems that especially the current gain of the lateral transistor can be affected in the desired direction by producing appropriate DL profiles because the current gain depends on the effective DL in the transistor base. So, a lower current gain and a higher latch-up immunity can be realized by stronger volume recombination (smaller $L_R$) and narrower denuded zones (smaller $w_{DZ}$) /45/. This is, however, in contradiction to the conditions required for realizing low junction leakage.

The discussed examples illustrate that there is, generally, a need of optimizing technological processes and resulting recombination properties in order to affect device properties favourably. Thereby, it is essential to utilize the acquired knowledge about the main recombination sources in heat-treated silicon. EBIC is a powerful technique for this purpose.
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