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OPTICAL CHARACTERIZATION OF THE CARRIER DISTRIBUTION IN SILICON POWER DEVICES WITH DEFINED SPATIAL RESOLUTION

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Abstract

Measured one-dimensional static recombination radiation intensity distributions of $P^{+}NN^{+}$ structures are compared to $p.n$ products yielded from a mathematical model. It is shown that the modelled data under correction for spatial resolution of the apparatus are in good qualitative agreement with measured data even in highly doped emitter regions.

Keywords: recombination radiation, carrier concentration, modelling, power diode.

Introduction

The recombination radiation as a tool for determining the excess carrier distribution has been widely used for studying silicon power devices such as diodes or thyristors.

For the first time it was used (KOKOSA, 1967) for a qualitative comparison of the on-state carrier distribution in the base(s) of diode and thyristor with the analytical model. Furthermore, studies on the on-state parameters of power rectifiers were continued (e.g. BURTSCHER et al., 1975) together with plasma spread studies in thyristors (e.g. SOMOS et al., 1970.). Recently, attention has been concentrated to studies on the GTO's failure mechanism (OHASHI et al., 1981) and to the homogeneity of the electrical behaviour of elementary thyristors working in parallel (HASHIMOTO et al., 1986).

Several authors (e.g. KRAUSSE, 1972, JÖRGENS, 1982) performed an experimental calibration of the theoretical relation between the intensity of recombination radiation ϕ (or output photodetector voltage) and the excess carrier concentration of electrons n and holes p

$$\phi = B \cdot n \cdot p, \tag{1}$$

where B is the so called recombination probability coefficient and for high injection conditions, when the principle of charge neutrality causes that

$n = p$, we can assume that

$$\phi = B \cdot n^2. \tag{2}$$

The above mentioned calibration is based on modifying *Eq. (2)* to the form

$$\phi = K \cdot n^c. \tag{3}$$

where K and c are constants to be determined experimentally. This experimental determination is carried out using other measuring methods not always applicable to the emitter regions. On the other hand it yields the absolute carrier concentration distribution. Frequently, the relative carrier concentration distribution is enough to solve the essential problems of power devices. During performance analysis of modern silicon power devices, like GTO thyristors, we are interested in the behaviour of both the base and emitter regions. If we compare the excess carrier concentration distributions yielded from both the measurements and modelling, we can observe that in the case of model distributions the transients from emitters into bases are very sharp (especially during the turn-off cycle). In the case of experiments, the mentioned sharp transients are quite well suppressed. Authors usually do not explain the reasons for this difference or consider effects like concentration dependent reabsorption, surface recombination, spatial resolution of the measuring apparatus. Description of this situation follows through the case of a P^+NN^+ power diode structure, but the results acquired are applicable not only to other structures like thyristors, but also to other measuring methods like the free-carrier absorption technique.

Experimental technique

The general principle of the measuring method is based on phonon assisted band to band recombination radiation mechanism included in the phenomenon called electroluminescence. The band to band recombination rate, expressed as concentration of recombined excess electrons n and holes p per unit time is

$$R = B_o \cdot n \cdot p. \tag{4}$$

R is therefore the number of photons emitted in volume V per unit time and is proportional to the $n \cdot p$ product. In case of charge neutrality ($n = p$) it is proportional to n^2.

In experimental arrangements the detector detects the radiation that goes through one side of the sample only, in $J \cdot m^{-2} \cdot s^{-1}$. This intensity is defined by *Eq. (1)* or *Eq. (2)*, where the coefficient B takes into account the

— frequency of radiation,
— temperature,
— absorption coefficient depending on
  — sample geometry
  — local carrier concentration
  — frequency of radiation,
— transmission coefficient of air-sample boundary, etc.

These facts together with the existence of recombination radiation on the absorption edge of silicon render impossible the analytical formulation of the coefficient B and make possible the experimental calibration of *Eq. (3)* only in order to get absolute carrier concentration distribution. In this case the concentration dependent reabsorption seems to be the dominant effect, that ought to be excluded by correction (SCHIERWATER, 1975). In the case of relative carrier concentration distribution measurements reabsorption also exists but without having a significant influence on the quality of the measured distribution as will be clear from the comparison of experimental and model distributions.

If we compare the recombination rates of the three main recombination mechanisms in a wide concentration range related to power devices, that are

— recombination via recombination centres,
— band to band recombination and
— Auger recombination,

it is obvious that the band to band recombination mechanism is never dominant. But still it carries true information about the carrier concentration which is evident from a comparison with the mathematical model.

The apparatus constructed for recombination radiation distribution measurements was based on the ordinarily used 'short focal length' arrangement (JÖRGENS, 1982). In order to excite recombination radiation, rectangular current pulses exceeding 100 μs were applied to a long P^+NN^+ diode structure sample. The radiation was localized through an optical path created by aperture diaphragm, objective lenses and localization slit, and collected by condensor onto a photomultiplier tube detector with S1 photocathode. The optical signal was digitized and processed by a computer. Spatial distribution was achieved by moving the excited sample against an unmoveable optical path. Spatial resolution was adjusted through the width of both the aperture diaphragm and localization slit. The setup described can afford not only a good spatial resolution, but due to the use of a photomultiplier tube, a good time resolution, too. Data acquisition technique without special signal to noise ratio improvement technique was based on simple averaging principle only, due to measurements performed with purposefully small spatial resolution.

Simulation technique

The mathematical model applied is based on solving the continuity and Poisson equations according to (KURATA, 1982) and takes into account

- — non-uniform doping profiles (Gaussian profiles due to the use of diffusion process),
- — carrier concentration and field dependent mobility and
- — SRH and Auger recombination process.

Since the recombination radiation profile measurements were carried out only in the centre of diode structure, it had no sense to take into account the effect of surface recombination and thus the employed model could be only one-dimensional. Appropriate values of lifetimes for SRH and Auger process formulas were acquired from fitting both OCVD (Open Circuit Voltage Decay) lifetime measurements and modelling with the same current densities at which recombination radiation distributions were measured. Some model parameters were fitted according to the measured *I-V* characteristics.

Results

Recombination radiation intensity distributions of a long P^+NN^+ structure under high injection conditions (current density varies from 1.7 A·mm^{-2} to 17 A·mm^{-2}) are shown in *Fig. 1*, where the units of the vertical coordinate are arbitrary due to relative measurements.

The corresponding $p \cdot n$ product distributions yielded from the mathematical model under the same conditions for the same structure are shown in *Fig. 2.*.

The qualitative disagreement is mainly due to the different values of spatial resolution of the apparatus and the model. Undoubtedly the spatial resolution of the model is zero μm compared to the experimental apparatus with spatial resolution every time higher than 20 μm due to the 1.1 μm wavelength of radiation and the big difference in refractive index of the air–silicon boundary. The spatial resolution is defined by FWHM (Full Width at Half Maximum) of the localized recombination radiation beam, whose spatial distribution shape is determined by a Gaussian curve. We can imagine the measurement process as localization of discrete recombination radiation beams from discrete positions within the sample with a concrete value of FWHM (it means spatial resolution) ordinarily higher than the spatial steps between two measured positions. If we perform a simulation of the measuring process starting from the data yielded by the mathematical model (*Fig. 2.*) and modifying these data through convo-

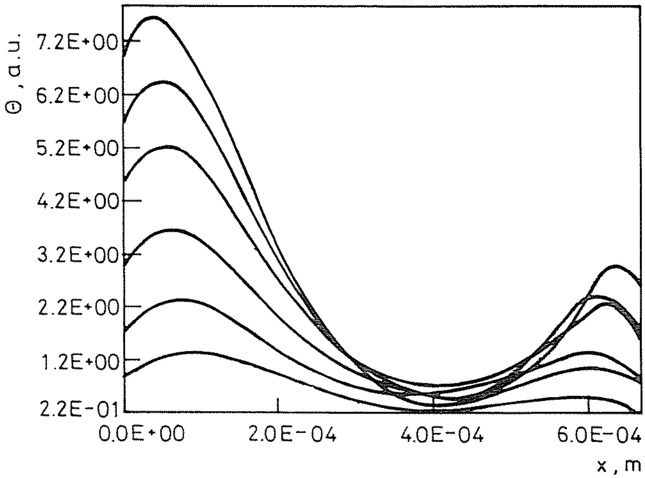

Fig. 1. Measured spatial distribution of recombination radiation intensity from power diode structure

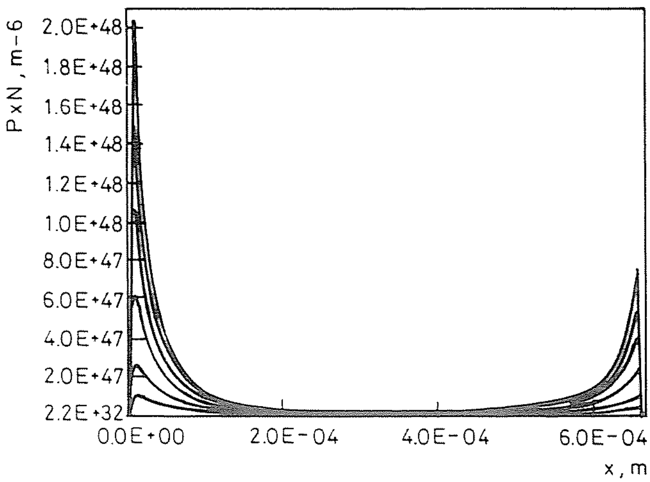

Fig. 2. $p \cdot n$ product spatial distribution corresponding to *Fig. 1* (yielded from mathematical model)

lution of the $p \cdot n$ product distribution function and the Gaussian curve function with constant optional FWHM value in every measured position x, we can get the distribution shown in *Fig. 3.*

This distribution is now in good qualitative agreement with the measured distribution and the value of FWHM was approximately 200 μm.

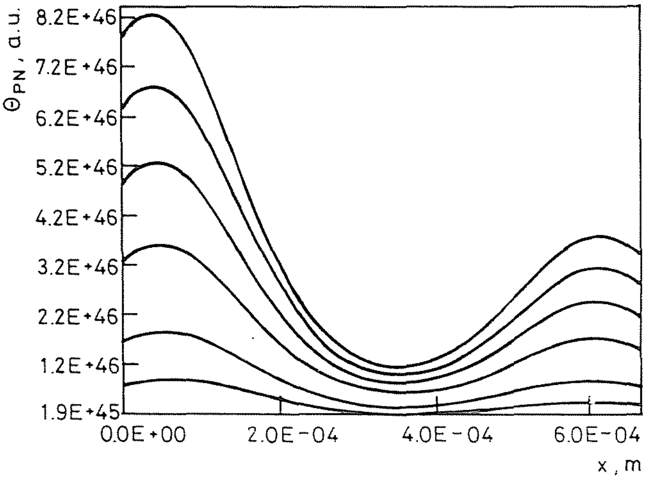

Fig. 3. Distribution from *Fig. 2* corrected by convolution process with spatial resolution 200 μm

Small differences in the right hand emitter part seem to be caused by contact modelling difficulties. From the qualitative point of view the choice of high FWHM clearly displays the influence of apparatus spatial resolution and undoubtedly it will be valid for lower FWHM (see *Fig. 4*) values, too.

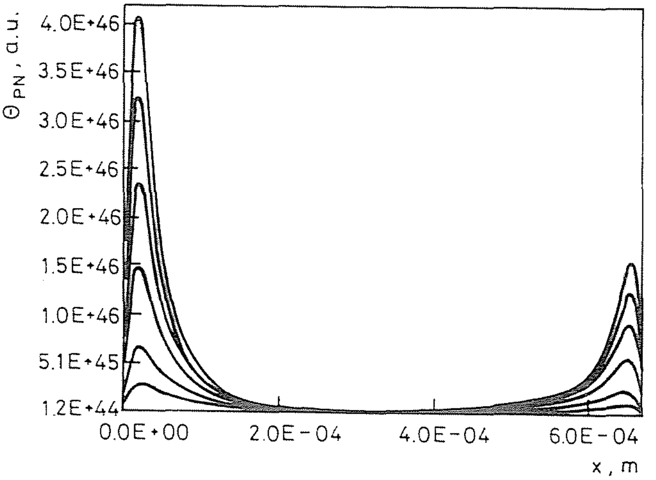

Fig. 4. Distribution from *Fig. 2* corrected by convolution process with spatial resolution 20 μm

Once more, *Fig. 3* shows the measurement simulation performed in two steps:
1) modelling the $p \cdot n$ product spatial distribution
2) simulation of the measuring process by accounting for the spatial resolution of the apparatus via convolution of both $p \cdot n(x)$ and Gaussian functions step by step in positions considered during the measurements.

Conclusions

It was shown how to fit the experimental and modelled data corresponding to the spatial distribution of the $p \cdot n$ product and how to determine the spatial resolution of the experimental apparatus. It is obvious that the described method is applicable to any arbitrary optical method with arbitrary value of spatial resolution, e.g. free-carrier absorption technique.

Furthermore, it is evident that in the case of relative recombination radiation intensity distribution measurements, the spatial resolution of the apparatus plays a dominant role in creating the shape disagreement between the measured and the modelled carrier concentration distributions.

Finally, here exists a potential possibility of an analogically reverse way to determine real concentration distribution from measured data. Undoubtedly this way is more complicated compared to the opposite way.

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