Scanning Microscopy

Volume 6 | Number 1 Article 4

10-25-1991

Electron Beam Induced Current Investigations of Electrical Inhomogeneities with High Spatial Resolution

Eu. Yakimov
USSR Academy of Sciences

Scanning Microscopy, Vol. 6, No. 1, 1992 (Pages 81-96, 80)
Scanning Microscopy International, Chicago (AMF O'Hare), IL 60666 USA

0891-7035/92$5.00+.00

ELECTRON BEAM INDUCED CURRENT INVESTIGATIONS OF ELECTRICAL INHOMOGENEITIES WITH HIGH SPATIAL RESOLUTION

Eu. Yakimov

Institute of Microelectronics Technology and High Purity Materials, USSR Academy of Sciences, 142432 Chernoglovka, Moscow District, Russia

(Received for publication June 26, 1991, and in revised form October 25, 1991)

Abstract

Electron beam induced current (EBIC) microscopy is a very promising SEM technique for the study of diffusion length and depletion region width inhomogeneities with high spatial resolution. However, this resolution is limited by the dimensions of the electron-hole pair generation region. In this paper the possibilities to improve spatial resolution are discussed. Electron beam tomography, i.e. the reconstruction of physical property distributions from sets of two-dimensional images, seems to be the most promising for this purpose. It is shown that in the case of dislocations it is possible to obtain information about dislocation impurity atmosphere parameters from EBIC measurements. The spatial resolution limitations in SEM techniques are discussed and it is shown that for many structures the spatial resolution is restricted by electron beam damage.

Key Words: electron beam induced current, diffusion length, semiconductor characterization, image contrast, microtomography, impurity atmosphere, carrier recombination, electron beam damage, depletion region width.

1. Introduction

Minority carrier diffusion length (L) and lifetime (τ) are important parameters which determine the characteristics of various types of semiconductor devices. For local measurements of these parameters and for a study of their spatial distribution the electron beam induced current (EBIC) microscopy is now widely used. In semiconductor crystals the parameters τ and L are very sensitive to a small amount of extended and point defects. This determines the possibility to reveal and to characterize the individual extended defects such as dislocations, grain boundaries, etc. as well as to study the spatial distribution of recombination centers when the change of their local concentration is as low as $10^{13} cm^{-3}$ ((Kittler and Seifert, 1981), (Aristov et al, 1988), (Bondarenko et al, 1988)) by EBIC. Such high sensitivity and high spatial resolution of this technique allows to consider it as a very promising method for characterization of submicron semiconductor structures.

In EBIC mode the finely focused electron beam of a scanning electron microscope (SEM) acts as a localized source of excess charge carriers. Then these nonequilibrium carriers diffuse through the crystal and if the sample under investigation contains any kind of internal electric field (for example, in the space charge region of a Schottky barrier) those carriers that reach the space charge region of the junction are collected by this junction and give the current in an external circuit. The number of collected carriers depends on the local lifetime τ and therefore the current measured in the EBIC mode is determined by the local value of τ. The basic principles and applications of the EBIC technique have been reviewed in a number of papers (see e.g., Hanoka and Bell (1981), Bresse (1982), Leamy (1982), Holt and Lesniak (1985), Dimitriadis (1988), Holt (1989)). Reviews dealing in

List of symbols

a	center of gravity of the depth-dose function (cm)
b	lateral resolution (cm)
C	contrast
c_e	probability of electron capture on dislocation (cm^3s^{-1})
D	minority carrier diffusion coefficient (cm^2s^{-1})
D^r_{min}	minimal radiation dose (cm^{-2})
D^r	radiation dose (cm^{-2})
d	electron beam diameter (cm)
E_b	electron beam energy (eV)
E_g	gap energy (eV)
E_i	energy of e-h pair formation (eV)
E_D	depth of the dislocation energy level (eV)
e	electronic charge ($1.6\ 10^{-19}$C)
$F(\bar{r},E_b)$	radial distribution of e-h generation (cm^{-2})
f	dislocation filling factor
$G(\bar{r})$	generation rate of the e-h pairs per unit volume ($cm^{-3}s^{-1}$)
G_o	total generation rate (s^{-1})
$h(z,E_b)$	depth distribution of the e-h generation (cm^{-1})
I_b	beam current (amps)
I_c	collected current (amps)
I_{c0}	collected current in defectless region (amps)
k	Boltzmann`s constant ($1.38\ 10^{-23}$ J/^{o}K)
L	minority carrier diffusion length (cm)
L_D	diffusion length in the defect region (cm)
N_{Au}	gold concentration (cm^{-3})
N_d	shallow level center concentration (cm^{-3})
N_D	density of centers along a dislocation (cm^{-1})
N_c	density of states in the conduction band (cm^{-3})
p	excess minority carrier concentration (cm^{-3})
R	primary electron range (cm)
$\bar{r}$	position vector (cm)
T	temperature (K)
t_m	metal thickness (cm)
x,y,z,v,ξ	spatial coordinates (cm)
V_D	defect region (cm^{-3})
U	applied voltage (V)
W	depletion region width (cm)
α	inclination angle
γ	accuracy of measurements
η	charge collection efficiency
θ	effective quantum yield
κ	fraction of the energy lost due to backscattered electrons
λ	recombination strength of a defect (cm^2s^{-1})
ν	material density (gm cm^{-3})
ρ	radius (cm)
ρ_d	radius of defect region (cm)
τ	minority carrier lifetime (s^{-1})
τ_d	minority carrier lifetime in the defect region (s^{-1})
φ	barrier height (V)
ψ	collection probability

more detail with the theoretical aspects of EBIC have been published by Donolato (1988, 1989).

Spatial resolution in the EBIC mode is determined by the dimensions of electron-hole generation volume and the diffusion length (Leamy, 1982) and in many cases has a value of some microns. Therefore to improve the spatial resolution it is necessary to carry out some additional measurements or use special processing of the images obtained. In the present paper some possibilities for increasing the spatial resolution in the EBIC mode and limitations for the spatial resolution of SEM techniques will be discussed.

2. Charge collection in EBIC mode

The primary electron beam impinging on the sample under study undergoes a successive series of elastic and inelastic scattering processes. As a result of these processes the focused electron beam spreads in the crystal and the region of electron-hole pairs generation has the dimensions comparable with the primary electron penetration depth R. This depth depends on the primary electron energy E_b and can be determined as $R = (\frac{4.57.10^{-6}}{\nu}) \times (E_b/1000)^{1.75}$, where ν is the material density (Everhart and Hoff, 1971) The distribution of electron-hole pairs generated by focused electron beam can be obtained by the Monte-Carlo simulation technique (see e.g., Napchan, 1989) or may be approximated by an analytical expression

$$G(\bar{r}) = G_0\ F(x,y,z,E_b)\ h(z,E_b) \qquad (1)$$

where $G_0 = E_b I_b(1 - \kappa)/eE_i$ is the total generation rate, I_b is the beam current, e is the electronic charge, $E_i = 2.596E_g + 0.714$ eV (see e.g. Wu and Wittry, 1978) is the energy required for the formation of an electron-hole pair , E_g is the gap energy, κ is the fraction of the electron beam energy lost due to backscattered electrons. It should be mentioned that in the case of a Schottky barrier κ essentially depends on E_b especially for small E_b or for a large metal thickness (see e.g., Niedrig (1982), Joy (1986), Aristov et al (1990a)). F(x,y,z) describes the radial distribution of e-h generation and for Si it is given by Donolato (1981)

$$F(x,y,z,E_b) = \frac{1.76}{2\pi\sigma^2 R} \exp[-(x^2+ y^2)/\sigma^2] \qquad (2)$$

where $\sigma^2=0,36d^2+0.11z^3/R$, d is the electron beam diameter. In GaAs the analytical approximation for F(x,y,z) was recently obtained by Konnikov et al (1987). The function $h(z,E_b)$ is the depth distribution of e-h generation and it can be approximated by the normalized expression proposed by Everhart and Hoff (1971)

$$h(z/R) = 0.6 + 6.21(z/R) - 12.40(z/R)^2 + 5.69(z/R)^3 \qquad (3a)$$

Other approximations were proposed for Si by Fitting et al (1977)

$$h(z/R) = (1.76/R)\ \exp[-7.5(z/R-0.3)^2] \qquad (3b)$$

and for GaAs by Wu and Wittry (1978)

$$h(z/R) = \exp\{-[(z/R - 0.125)/0.35]^2\} - 0.4\ \exp(-4z/0.125R) \qquad (3c)$$

The electron beam induced current collected by a Schottky barrier or p-n-junction is determined by the excess minority carrier three-dimensional distribution which depends not only on the generation but also on diffusion and recombination processes. Under steady state conditions and at low excitation levels this distribution can be obtained by solving the differential equation

$$\nabla^2 p(\bar{r}) - p(\bar{r})/L^2(\bar{r}) + G(\bar{r})/D = 0 \qquad (4)$$

where p is the excess minority carrier concentration, D is their diffusion coefficient. In the case of a Schottky barrier the boundary conditions are $p(x,y,W) = 0$ and $p \to 0$ for $z \to \infty$, where W is the depletion region width. The collected current is given by

$$I_c = eD \iint \frac{\partial p}{\partial z}(x,y,W)\,dxdy \qquad (5)$$

It is also possible in accordance with Donolato (1985a, 1988) to calculate I_c as

$$I_c = e \int G(\bar{r})\psi(\bar{r})\,d\bar{r} \qquad (6)$$

where $\psi(\bar{r})$ can be obtained by solving the equation

$$\nabla^2\psi(\bar{r}) - \psi(\bar{r})/L^2(\bar{r}) = 0 \qquad (7)$$

with boundary conditions $\psi(x,y,W) = 1$ and $\psi \to 0$ for $z \to \infty$. The function $\psi(\bar{r})$ is the charge collection probability and it represents the collected current produced by a unit charge situated at $\bar{r}$. It is usually assumed that $\psi = 1$ inside depletion region, i.e. that a recombination in this region can be neglected. The other boundary conditions and a recombination inside depletion region was discussed by Tabet and Tarento (1989).

3. Measurements of diffusion length and depletion region width

3.1. Stationary methods for homogeneous materials

It follows from (7) and the assumption $\psi = 1$ at $z < W$ that for homogeneous samples

$$\psi(z) = \begin{cases} \exp\ [-(z-W)/L] & z > W \\ 1 & z \le W \end{cases} \qquad (8)$$

In this case

$$I_c = \int_W^{\infty} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} G(\bar{r}) \exp[-(z-W)/L] dxdydz + \int_{t_m}^{W} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} G(\bar{r}) dxdydz = \int_W^{\infty} h(z) \times \exp[-(z-W)/L) dz + \int_{t_m}^{W} h(z) dz \qquad (9)$$

where t_m is the metal thickness. From (9) it follows that if L does not depend on z and if L and W are not essentially changed at the distances smaller than R then local changes of I_c are determined by the spatial distribution of L and W. Therefore, it is possible to obtain L and W and their two-dimensional distribution from the measurements of $I_c(E_b)$ by comparison of the experimental results with those of numerical calculation using (9) ((Kamm, 1976), (Wu and Wittry, 1978), (Chi and Gatos, 1979), (Frigeri, 1987)).

The other stationary methods for the diffusion length determination are associated with measurements of collected current decrease with a distance to the depletion region of the junction parallel to the beam (see e.g., Van Roosbroeck (1955), Higuchi and Tamura (1965), Berz and Kuiken (1976), van Opdorp (1977), Oelgart et al (1981)) or to the edge of the junction perpendicular to the beam ((Ioannou and Davidson, 1979), (Ioannou and Dimitriadis, 1982), (Kuiken and van Opdorp, 1985), (Artz, 1985), (Donolato, 1985b)). The method of the diffusion length determination based on the analysis of the EBIC contrast profiles of grain boundaries parallel to the beam was proposed by Donolato (1983a). In these spatial decay methods the main disadvantage is associated with a surface recombination, which influences the dependences measured.

This problem does not exist in the methods based on the measurements of the $I_c(E_b)$ dependence. But in this case it is possible to obtain L and W only if W is comparable with L or R (for calculations of W) or if L < R (for measurements of L). To overcome these disadvantages it is necessary to increase the precision of measurements. The other disadvantage of this method -- very high time consumption - can be overcome using the method proposed by Kittler et al (1989), in which the penetration depth variation is realized by inserting a wedge-shaped absorber between the primary beam and the sample to be measured.

3.2 Modulation methods

Measurements using the modulation of one of the parameters and the phase sensitive detection technique (Balk et al, 1975) provide additional possibilities for the semiconductor characterization by EBIC. One of such possibilities is associated with the phase shift measurements using a modulated electron beam ((Kamm and Bernt, 1978), (Fuyuki and Matsunami, 1981), (Konnikov et al, 1990)). By this technique it is possible to obtain not only L but also τ. Measurements of the spatial derivative of I_c by the modulation technique (Parsons et al, 1979) are also very useful. Indeed, as was shown by Luke et al (1985), the value of $d/dx\ \{\log[I_c(x)]\} = \frac{dI_c}{dx}/I_c$ is less sensitive to a form of the generation function used for the calculation than I_c.

Recently it was shown by Kononchuk and Yakimov (1991) that the measurements of the dI_c/dW value in combination with I_c are very useful for the determination of L and W values. Indeed, it is easy to show that for homogeneous samples

$$\frac{dI_c}{dW} = \int_W^{\infty} \frac{d\psi}{dW} h(z) dz = \frac{1}{L} \int_W^{\infty} \psi\, h(z) dz = \frac{1}{L} (I_c - \int_0^W h(z) dz) \qquad (10)$$

From such expression it is possible to obtain L and W from the measurements of I_c and dI_c/dW at two beam energies E_b. This technique is very promising also for mapping these parameters. It should be mentioned here the possibility to map the depletion region width W by the electron beam induced capacitance technique which can be used for a wide range of relations between L, W and R (Aristov et al, 1990b)

3.3 Methods for inhomogeneous materials

In some cases L is inhomogeneous only in depth from the surface. For example, it takes place after such technology processes as internal or external gettering (see e.g., Donolato and Kittler, (1988)) , dry etching (Koveshnikov et al, 1989), etc. If the distribution of recombination centers can be described in a parametric form as in the case of reactive ion etching (RIE) of gold-doped Si, it is possible to obtain the distribution of L by comparison of the experimental dependence of charge collection efficiency $\eta = I_c/eG_0$, i.e., the fraction of the induced charge which is collected by the Schottky barrier, on E_b with a calculated one. In this case gold is gettered from the subsurface layers (Koveshnikov et al, 1989, 1990) and is distributed as

$$N_{Au} = N_{Au0}[1+B\exp(-z/z_0)]^{-1} \qquad (11)$$

where N_{Au} and N_{Au0} are the gold concentrations in the etched and untreated crystals, respectively, B and z_0 (z_0 ~ 1μm) are some parameters which depend on etching conditions. From (11) it is easy to show that

$$\frac{1}{L^2(z)} = \frac{1}{L_0^2} + \frac{1}{L_{Au}^2}[1 + B\exp(-z/z_0)]^{-1} \qquad (12)$$

where L_0 is the diffusion length in the same crystal but without gold, L_{Au} is the diffusion length associated with gold. Comparison of experimental results with calculated ones obtained by solving Eqs.(6) and (7) with L(z) obtained from (12) gives the possibility to obtain L_0, z_0 and B, i.e., L(z) (Fig 1). The other

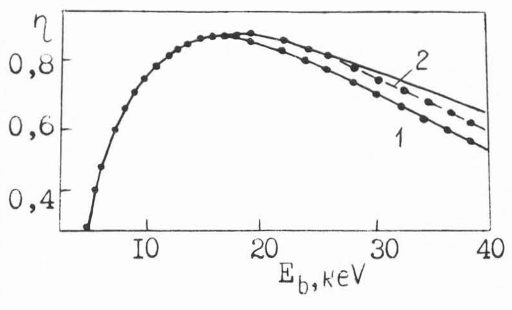

Fig.1. Dependence of the charge collection probability η on E_b for a Schottky barrier formed on as-grown Fz-Si<Au> (1) and on the same crystal after plasma etching (2). The solid curves are calculated using (6) and (7) with L = 4.5 and 8 μm, respectively. The dashed line is the best fitting using (12) with B = 26.3; z_0= 2.25 μm; L_0= 9 μm and L_{Au}= 5.2 μm.

example of such a reconstruction was given by Possin and Kirkpatrick (1979) on ion-implanted Si. In a similar way it is possible to obtain from the $I_c(E_b)$ dependence the depth of point-like defects (Mil'vidskii et al, 1985) or dislocations (Milshtein et al, 1984).

In the case of unknown L(z) dependences Donolato and Kittler (1988) proposed a procedure for depth profiling of the diffusion length from EBIC measurements on beveled samples. Under the assumption that W = 0 and that the electron beam excitation volume is represented by point source at the center of gravity a of the depth-dose function it was shown that

$$L(v + a/2) \approx f(v)\,[1 + f'(v)]^{-1/2} \qquad (13)$$

where $v = \zeta \sin\alpha$ is the depth , ζ the is position of the electron beam on an axis along beveled surface, α is angle on which the sample is beveled and f(v) = $= -a/\log[\eta(v)]$. $\eta(v)$ is the charge collection probability when electron beam is situated at ζ and can be obtained from experimental results. In this paper also was proposed a generalization of the reconstruction procedure to an extended generation region and a nonzero width of the depletion layer.

A more general consideration of the problem of the diffusion length distribution reconstruction from EBIC measurements (EBIC tomography) was proposed by Donolato (1989) and Zaitsev and Samsonovich (1990). Zaitsev and Samsonovich (1990) have shown that it is possible to transform the nonlinear equation describing the signal formation in the EBIC mode to a linear Fredholm integral equation (the procedure proposed by Donolato (1985a) is the other example of a transformation to a linear equation). Therefore to solve the inverse problem, i.e. to reconstruct the three-dimensional distribution of diffusion length, it is necessary to solve this Fredholm equation. The problem of the solution of this equation is ill-posed but it can be solved by the well developed regularization method (Tichonov and Arsenin, 1977). To reconstruct the diffusion length distribution it is necessary to measure a set of two-dimensional images with different values of a third variable (e.g., E_b). The example of such reconstruction was recently given by Bondarenko et al (1990). It has been also shown (Zaitsev and Samsonovich, 1990) that the same procedure can be applied to time resolved EBIC (TREBIC) (Spivak et al, 1977) with time as a third variable for reconstruction. Of course, TREBIC allows one to improve the spatial resolution without any mathematical treatment (Georges et al, 1980, 1982) but such a microtomography procedure gives additional possibilities for the reconstruction of the diffusion length distribution.

4. Spatial resolution in EBIC measurements

The spatial resolution in EBIC mode

is determined by the values of R and L. Therefore to increase a spatial resolution it is necessary to decrease R by decreasing E_b and this gives a possibility at small enough E_b to achieve a resolution in submicron range. But the question is about the possibility to achieve spatial resolution better than the R and L values. For one- and two-dimensional defects the image width is determined mainly by R and only slightly degraded by an increase in L (see e.g. Donolato (1979) and Leamy (1982)). In this case the resolution can be much better than L. Moreover, the defect image width can strongly decrease when the defect is situated inside the depletion region (Kittler, 1980).

In spatial decay technique like methods it is possible to measure L values at L≥R/4 (Luke et al, 1985). When the $I_c(E_b)$ dependence is used for L and W measurements the lateral resolution is determined by L and R but the resolution in depth can be better than R and L and depends on an accuracy of measurements. Modulation methods give a possibility to increase the accuracy of small I_c change measurements and therefore to increase the depth resolution. For example, in one-dimensional case Possin and Kirkpatrick (1979) using parametric expression for the L(z) dependence achieved the resolution in depth about 0.1 μm. It seems that in the case of a three-dimensional variation of L the electron beam tomography provides the best possibilities for the L reconstruction. In principal, it is possible to achieve the spatial resolution about 0.1 of R, of course, if the measurement accuracy is high enough. It should be noted that it is only possible to achieve the spatial resolution better than R if E_b is used as a third variable. The spatial resolution of TREBIC images can be improved only when they are smoothed by a diffusion process because the e-h generation is a very fast process and it is very difficult to resolve generation region formation kinetics by time-resolved measurements.

There are a lot of possibilities to improve the spatial resolution in measurements of different geometrical parameters of semiconductor structures (see e.g., Shick (1985), Marten and Hildenbrand (1985), Hoppe and Kittler (1989)) but this question will not be discussed in the present paper.

5. EBIC investigations of dislocations

5.1. Defect region around dislocations

In this chapter the results of dislocation studies are analyzed in more detail to show the possibility to obtain some additional information about the properties of the regions with dimensions smaller than R.

It was usually believed that the dimensions of the dislocation defect region in the crystal are much smaller than the contrast width of this dislocation on the EBIC image and therefore in the model Donolato,1978,1983 a,b)describing a dislocation as a row of noninteracting recombination centers the recombination activity of a dislocation is characterized by the recombination strength $\lambda = \frac{\pi\rho_d^2}{\tau_d}$ where ρ_d is the radius of the defect region around the dislocation and τ_d is the minority carrier lifetime inside this region. From the assumption that the recombination centers are situated in the dislocation core it follows that the exact values of ρ_d and τ_d have no physical sense. In accordance with this it follows that it is possible using experimental results to obtain λ but impossible to separate ρ_d and τ_d and therefore it is impossible to obtain an information about the internal structure of dislocation defect region from the EBIC measurements. But in real crystals ρ_d for uncharged dislocations describing by the Donolato model can be larger than dislocation core dimensions. The reason for the large enough defect regions around dislocations is the formation of point defect atmospheres around them. The influence of such atmospheres on the dislocation recombination properties was observed in a lot of papers (see e.g., Blumtritt et al (1979), Menninger et al (1980), Castellani et al (1982), Bondarenko et al (1986), Aristov et al (1987), Sieber (1989)). The dislocation point defect atmosphere properties strongly depend upon the deformation and subsequent thermal treatment conditions, dislocation type, impurity content, etc. In this case the measurements of ρ_d and τ_d values can give a knowledge about the properties of such atmospheres.

Recently Pasemann (1991) on the base of EBIC contrast calculations has shown for surface perpendicular uncharged dislocation that in principal it is possible to obtain ρ_d and τ_d from the dependence of the contrast value on electron beam energy but only in the case when R is comparable with ρ_d. Nevertheless, it proves to be that in principal it is possible to obtain these values even when ρ_d is much smaller than R. For example, the evaluation of ρ_d and τ_d values was obtained by Weber et al (1989) from the measurements of the contrast dependence on dislocation depth by the method proposed by Kaufmann et al (1987). The comparison of experimental results with those of numerical simulation has shown that in GaAs the radius of the defect cylinder is about 50 nm, i.e. it is much smaller than R but large than dislocation core dimensions.

The other reason for large enough ρ_d value is associated with the space charge cylinder formed around a charged dislocation. Such dislocations can not be described by the Donolato model and to describe them it was assumed that $p(\rho) = 0$ at $\rho < \rho_d$ ((Castaldini et al, 1985), (Cavallini and Gondi, 1987)). Then ρ_d has an obvious physical sense and is equal to the value calculated by Read (1954) with $\tau_d \approx 0$ inside this cylinder. Thus, it is not easy to choose an appropriate model for a correct description of the EBIC profile of a dislocation in a real crystal and its dependence upon electron beam parameters. To understand the main features of such models it is necessary to have a knowledge about the dislocation charge and about the state of its impurity atmosphere.

For these purpose the EBIC investigations of dislocations introduced at a low enough temperature, the impurity atmosphere of which was changed by the subsequent thermal treatment and the crystal impurity content, were carried out by Bondarenko and Yakimov (1988, 1990). The impurity atmosphere state was controlled by measurements of starting stresses which were very sensitive to the existence of impurity complexes near the dislocation (Bondarenko et al, 1980). To control the dislocation charge in accordance with Wilshaw and Booker (1987) and Bondarenko and Yakimov (1987) the contrast dependence on the beam current was measured and the results of I-V characteristic measurements on microcontacts to dislocation edge pits (Mil'shtein and Nikitenko, 1971), (Eremenko et al, 1975) were used. It has been shown that dislocations introduced by the plastic deformation in the temperature range from 600 to 700^0C are charged and space charge cylinders are formed around these dislocations. After annealing at $T \geq 850^0$C dislocations in n-type Czochralski Si (Cz-Si) do not have space charge cylinders but the EBIC contrast of such dislocations is rather high and may reach 15-20%. It has been observed that the dislocation contrast in Si crystals strongly depends on the impurity atmosphere state for the charged as well as uncharged dislocations, i.e. some volume with a high concentration of recombination centers exists around the both types of dislocations. Therefore the question arises of the possibilities to determine the characteristics of this region from the EBIC measurements.

5.2. Investigations of uncharged dislocations in Si

The dependence of the EBIC contrast C of uncharged dislocations on electron beam current is relatively weak (Fig.2, curve 5) and differs from that observed on dislocations with a potential barrier (Fig.2, curves 1-4). It was found that for such dislocations the derivative $dC/dW = (dC/dU)/(dU/dW)$, where U is the voltage applied to the structure, is a curve with a maximum and correlates well

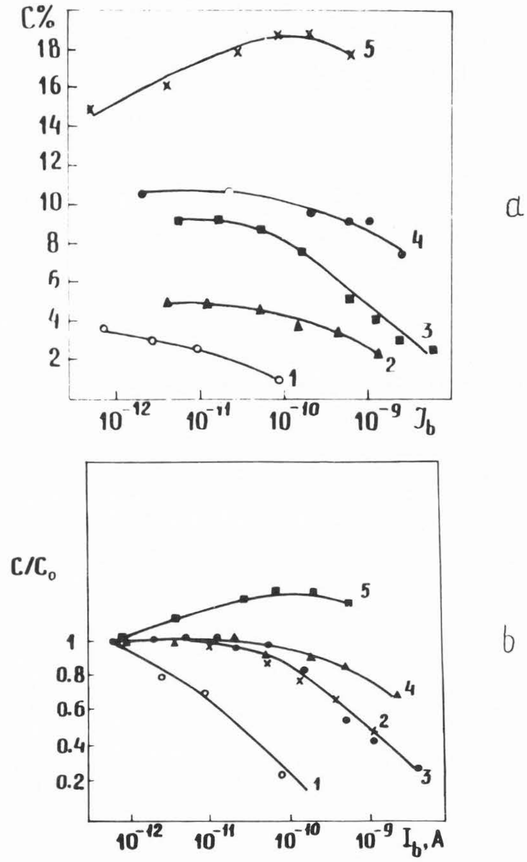

Fig.2. a- Dependence of contrast on beam current for dislocations after 600^oC deformation (1-4, curve 3 for quenched sample) and subsequent 900^0C annealing (5). Curve 1 is for Cz-1; curves 3,4,5 are for Cz-2, curve 2 is for Fz-Si doped with Au (Bondarenko and Yakimov, 1990).
b- Dependence of the normalized contrast C/C_0 on beam current for the same dislocations. C_0 is the contrast value obtained at the smallest for every curve beam currents.

with the h(z) function up to a depth z ~ 1,8 μm (Fig.3). For dislocations perpendicular to the surface in accordance with Donolato (1983) neglecting the influence

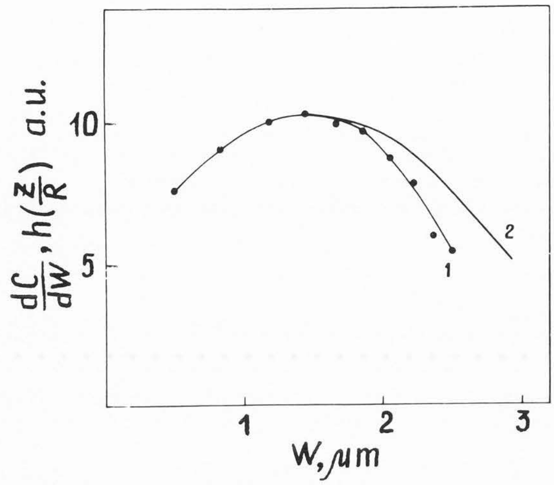

Fig.3. Derivative of the contrast versus depth for an annealed dislocation in Si (1). 2- depth distribution of the generation function h(z).

of a part of the dislocation situated inside the depletion region the contrast is given by

$$C = 1 - I_c/I_{c0} = 1 - (2\pi \int_0^W \int_0^\infty G(\bar{r})\rho d\rho dz + 2\pi \int_W^\infty \int_0^\infty G(\bar{r})\psi(\bar{r})\rho d\rho dz)/I_{c0} \quad (14)$$

and

$$dC/dW = -(2\pi/I_{c0}) \int_W^\infty \int_0^\infty G(\bar{r}) d/dW\, [\psi(\bar{r})]\rho d\rho dz \quad (15)$$

where I_{c0} is the current collected when the beam is far from the dislocation. That is, the both C and dC/dW are proportional to the integrals over the region with dimensions about L_D due to the exponential dependence of ψ on L_D. But as mentioned above, for such dislocations dC/dW is proportional to h(z/R) (Fig.3). Thus, the coincidence of the h(z/R) and dC/dW curves can be only explained under the assumption that the diffusion length L_D is very small near the dislocation. In this case

$$dC/dW = -(2\pi/I_{c0}) \int_W^{W+L_D} \int_0^\infty G(\bar{r}) d/dW\, [\psi(\bar{r})] \times \rho d\rho dz = -(2\pi/I_{c0}) \int_0^\infty G(\rho, W + L_D/2) \times d/dW\, [\psi(\rho, W + L_D/2)]\rho d\rho \sim -h(W + L_D/2)/I_{c0}L_D \approx -h(W)/I_{c0}L_D \quad (15a)$$

Since annealed dislocations are surrounded by point defect precipitates it is possible to describe such dislocations by Donolato's model (Donolato, 1978, 1983a,b) suggesting that cylinders around them with radius ρ_d actually exist. A numerical solution of the diffusion equations with such a dislocation model and a comparison of calculated C(W) and dC(W)/dW dependences with measured ones gives for $L_D \sim 0.1$ μm and for $\rho_d \sim 0.1$ μm.

Using the value of L_D obtained it is possible to evaluate the concentration of recombination centers near dislocation which was found to be about 10^{18}-10^{19} cm^{-3}, i.e. about 10^9-10^{10} centers per cm along the dislocation line, and correlates with the results obtained by Bondarenko et al (1980). Of course, it is possible to obtain from EBIC measurements the parameters of the dislocation impurity atmosphere only in the frame of some assumptions, e.g. the values discussed were obtained under assumption that inside this cylinder τ_d = const. Thus, this method as well as that proposed by Weber et al (1989) gives a possibility to obtain information about the parameters of a region with dimensions much smaller than the primary electron penetration depth R only under some assumptions about the spatial distribution of recombination centers inside this region which can be made on the base of other experiments or theoretical considerations.

5.3. Properties of charged dislocations in Si

In the case of charged dislocations the situation is more complicated. First of all for such dislocations dC/dW does not correlate with h(z) which could be evidence that τ_d is not equal to 0 inside space charge cylinder around such dislocation segments or that an essential part of the contrast is associated with dislocation segments situated inside the depletion region of a Schottky barrier. Besides the contrast value of such dislocations depends on the impurity atmosphere state. The dependences of the dislocation contrast on beam current in the samples with different impurity content are shown in Fig.2. In accordance with Wilshaw and Booker (1987) and Bondarenko and Yakimov (1987) the decrease of contrast on curves 1-4 with increasing beam current is determined by the barrier near the dislocations. It should be stressed that the difference between curves 3 and 4 were obtained for dislocations introduced under the same conditions but cooled under different conditions. Quenching of deformed samples or cooling them under load leads to a decrease of the contrast value as well as to a change in its dependence on beam current. Since quenching also results in a significant decrease of the starting stress by decreasing the number of point defect complexes near the dislocation (Bondarenko et al, 1980) the difference observed shows that dislocation contrast is associated with such complexes.

It is easily seen from Fig.2 that the contrast is constant up to the some value of I_b which depends on the sample under investigation and at higher I_b decreases approximately logarithmically with I_b. The investigations of the temperature dependence of the charge carrier concentration and the dislocation density at which conductivity type inversion in n-Si was observed showed (Eremenko et al, 1978) that in n-Si with equal phosphorus concentration the barrier height is the same for the both Cz-Si and floating zone Si (FZ-Si). Thus the contrast value essentially depends on the state of the dislocation point defect atmosphere at practically unaltered barrier height. It was observed also (Bondarenko and Yakimov, 1990) that for dislocations introduced at 600^{o}C an increase of an impurity content in the dislocation atmosphere leads not only to an increase of the contrast value but also to an increase of the I_b value at which the contrast begins to decrease with increasing I_b (Fig.2), i.e. the stability of the dislocation charge under electron beam excitation depends on the impurity atmosphere state. These results contradict Wilshaw model of the EBIC contrast for charged dislocations ((Wilshaw and Booker, 1987), Wilshaw et al, 1989), Wilshaw and Fell, 1989)) in which the EBIC contrast is proportional to the dislocation barrier height φ

$$\varphi = \frac{kT}{e} \ln \frac{c_e N_D (1-f) N_d}{c_e N_D f N_c \exp(-E_D/kT) + k_1 I_b} \qquad (16)$$

where c_e is the probability of electron capture on the dislocation state, N_D is the density of centers along dislocations, N_d is a shallow impurity concentration, f is the filling factor of dislocation centers, N_c is the energy state density in conduction band, E_D is the depth of the dislocation energy level, k_1 is the proportionality coefficient between the beam current and the hole flow to the dislocation.

To explain this contradiction Bondarenko and Yakimov (1990) take into account that besides the centers with energy level situated at 0.44 eV from the valence band (Eremenko et al, 1977), a set of other energy levels was observed in plastically deformed Si ((Kimerling and Patel, 1979), (Kveder et al, 1982), (Bondarenko et al, 1986)). If it is assumed that some of this dislocation related centers can effectively take part in the recombination processes and practically do not change the radius of the space charge cylinder around the dislocation, then a change in the concentration of such centers involves a change of part of the total flow of holes, recombining through the N_D centers and, in turn, affects the dependence of the filling factor of N_D centers on I_b and, hence, the I_b range in which the barrier height is independent of I_b. Such properties may be associated with the centers situated at some distance from the dislocation. It should be mentioned that the distribution of dislocation centers also allows the theory to account for the observation of the spectrum of dislocation energy levels by DLTS ((Kimerling and Patel, 1979), (Kveder et al, 1982), (Bondarenko et al, 1986)).

In this model it is necessary to assume that near the edge of Read`s cylinder the recombination center concentration is about 10^{17}-10^{18}cm^{-3} but the recent DLTS data (Koveshnikov et al, 1991) show that the concentration of deep level centers in this region is much lower. In this paper it was also shown that the impurity center concentration near the dislocations is so high that there is a plateau of electrostatic barrier near the dislocation core in Si. This gives a possibility to explain the contrast difference as well as the enormous difference in the critical value of beam current at which the EBIC contrast starts to decrease. It can be assumed that the critical value of beam current corresponds to that radius of Read's cylinder which is approximately equal to the size of e-h pair generation region. Taking into account that radia of Read's cylinder without electron beam have approximately the same values in the crystals of various purity it is necessary to accept that the difference in the position of the bending point is determined by different stability of the barrier under excitation. The change of the total dislocation charge is mainly determined by the sweep of the excess electrons from Read's cylinder. It is clear that the higher concentration of recombination centers in Cz-Si ensuring the higher contrast decreases simultaneously the probability of electron to be swept out of Read's cylinder and makes the barrier more stable.

6. Spatial resolution limitations due to electron beam damage

To increase the spatial resolution it is necessary to increase irradiation dose because as shown by Aristov et al (1988) and Bondarenko et al (1988) the minimal irradiation dose D^r_{min} is equal to

$$D^r_{min} = \frac{1}{\gamma^2 b^2} (\delta+\beta/\theta) \qquad (17)$$

where γ is the necessary accuracy of measurements, b is the necessary lateral resolution, θ is the effective quantum yield of the method used, δ and β are constants ($\delta \sim \beta \sim 1$). That is, to increase the lateral resolution, i.e. to diminish b, it is necessary to increase D^r as $1/b^2$. The increase of D^r is also necessary for depth profiling with high resolution. Electron beam microtomography, i.e. the reconstruction of the diffusion length distribution by image processing, needs high doses because for this procedure a set of images obtained for example with different E_b is used and the accuracy of the measurements must be very high (Zaitsev and Samsonovich, 1990). But in many cases the value of D^r is limited. It can be limited for example by the time of investigation if it is impossible to increase the electron beam current. For some structures the value of D^r is limited by radiation damage under the electron beam. For example Si-SiO_2 structures change their properties noticeably after irradiation with a dose $\sim 10^{13} cm^{-2}$ ((Nakamae et al, 1981), (Gorlich and Kubalek, 1985), (Reiners et al, 1985), (Hungerford and Holt, 1987)). The detailed mechanism of this damage is not yet known but the experimental results obtained by Gorlich and Kubalek (1985) and Reiners et al (1985) show that x-ray irradiation takes part in the formation of the changes observed.

Semiconductor single crystals are more stable under electron beam irradiation than Si-SiO_2 structures but in some compound semiconductors pronounced changes in properties were observed as a result of electron beam excitation in SEMs. Thus it was observed by Bogdankevich et al (1987) that after electron irradiation with a beam energy of 5 keV and a dose about $10^{16} cm^{-2}$ the cathodoluminescence intensity of CdS was changed. In CdHgTe crystals after irradiation with dose 10^{18} - $10^{19} cm^{-2}$ the composition of subsurface layers was changed ((Nitz et al, 1981), (Shih et al, 1986), (Zaporozchenko et al, 1985a, 1985b)) and at dose about $10^{17} cm^{-2}$ Panin and Yakimov (1989) observed a change of electrical properties.

In this case the electrical properties were changed at distances up to 100 μm from the beam position along the surface and some μm in depth (Fig.4). The

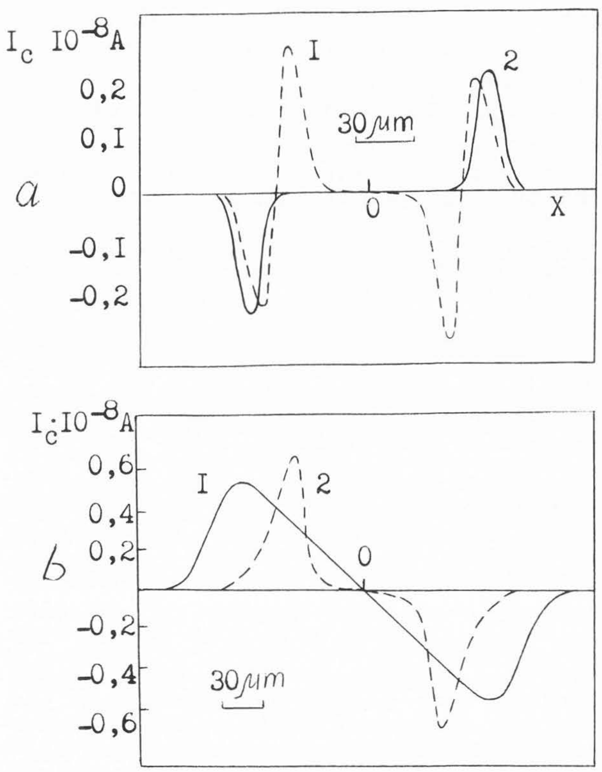

Fig.4 REBIC profiles obtained on CdHgTe after electron beam irradiation (Panin and Yakimov, 1989).
a - p-type crystal, irradiation time t_{ir}= 5s (1) and 1s (2)
b - n-type crystal, t_{ir}= 2s (1) and 10s (2)
E_b= 25 keV, I_b= 10^{-7}A, 0 - electron beam position during irradiation.

investigations were carried out by remote contact EBIC (REBIC) method which is very suitable for in-situ investigations of the local electrical property changes under the electron beam irradiation in SEM. In this method the electron beam induced current is measured in the geometry with two ohmic contacts formed at two opposite remote ends of the sample and it gives possibilities to reveal the charged inhomogeneities (see e.g., Panin and Yakimov, 1991). The results obtained show that near the surface a heterojunction is formed and in n-type crystals besides this heterojunction a p-n junction is formed and the boundaries of these junctions, i.e., the boundaries of regions with changed electrical properties and/or composition are revealed. With increase of the radiation dose some grooves can be produced on the surface of different crystals (Yegorshev et al, 1989).

The electron beam can significantly change the properties of extended defects. Thus in CdHgTe crystals, a decrease of the minority carrier diffusion length near a grain boundary as a result of electron beam irradiation is observed at a dose an order of magnitude smaller than in a defect free region (Panin and Yakimov, 1989). The restoration of the EBIC contrast of extended defects in hydrogen passivated Si was observed by Yacobi et al (1984a, 1984b) at a dose of about $10^{15}cm^{-3}$. At higher irradiation doses and beam currents the electron beam can enhance dislocation mobility in compound semiconductors (Maeda et al, 1983). All these results show that for some kinds of defects and semiconductor structures the irradiation dose during investigation must be limited to avoid changing the properties of the object under investigation.

It can be seen from (17) that the irradiation dose needed to achieve a particular spatial resolution depends on the effective quantum yield θ of the method used. From this point of view methods with higher value of θ such as EBIC are more promising for investigations with high spatial resolution than e.g. the SE mode or X-ray microanalysis. Therefore it is very important to find possibilities for obtaining additional information about the properties of defects under study from EBIC measurements. In any case the first step to overcome the limitations associated with radiation damage is to choose the appropriate technique with the higher quantum yield. Then it is possible to choose the appropriate experimental conditions in which such damage is minimal. For example to minimize the damage of $Si\text{-}SiO_2$ structures, a very low energy of electron beam was used (Reiners, 1990) but it is not possible in all cases. Studies of the mechanisms of electron beam damage under irradiation by electrons with subthreshold energy will help to choose such conditions. The other possibility is to study the kinetics of changes of the measuring property and then extrapolate the results observed to the beginning of measurements.

7. Conclusion

The possibilities to improve the spatial resolution in SEM-EBIC mode are discussed. Electron beam tomography, i.e. reconstruction of three-dimensional distribution of minority carrier diffusion length by procession of a set of two-dimensional EBIC images is the most promising method for this purpose. It gives a possibility to improve spatial resolution up to R/10. But besides development of special mathematical procedures it needs essential improvement of accuracy of measurements. The possibilities of increasing spatial resolution in some special cases are discussed. It is shown that in all cases the improvement of spatial resolution leads to increase electron beam irradiation dose that in turn limits the spatial resolution. Our estimations show that due to its high effective quantum yield EBIC mode is the most promising one for characterization of submicron structures. Therefore search of ways of spatial resolution improving and obtaining information about characteristics of defects which determine revealed by EBIC inhomogeneities is very important.

References

Aristov V V, Bondarenko I E, Heydenreich J, Khodos I I, Snighireva I I, Werner P, Yakimov E B, Yarykin N A (1987) Electrical Properties and Defect Structure of Plastically Deformed Silicon Crystals Doped with Gold. Phys. Stat. Sol. (a)102, 687-695.

Aristov V V, Kazmiruk V V, Ushakov N G, Yakimov E B, Zaitsev S I (1988) Scanning electron microscopy in submicron structure diagnostics. Vacuum. 38, 1045-1050.

Aristov V V, Dryomova N N, Likharev S K, Rau E I (1990a) Scanning electron microscopy in diagnostics of semiconductor structures. Electronnaya promyshlennost, No 2, 44-46 (In Russian).

Aristov V V, Kononchuk O V, Rau E I, Yakimov E B (1990b) SEM investigation of semiconductors by the capacitance techniques. Microelectronic Engineer. 12, 179-185.

Artz B E (1985) Electron-beam-induced current determination of minority-carrier diffusion length and surface recombination velocity in mercury-cadmium-telluride. J.Appl. Phys. 57, 2886-2891.

Balk L J, Kubalek E, Menzel E (1975) Time Resolved and Temperature Dependent Measurements of Electron Beam Induced Current (EBIC), Voltage (EBIV) and Cathodoluminescence (CL) in the SEM. Scanning Electron Microsc. 1975; 447-455.

Berz F, Kuiken H K (1976) Theory of Lifetime Measurements with the Scanning Electron Microscope: Steady State. Solid-State Electron. 19, 447-455.

Blumtritt H, Gleichmann R, Heydenreich J, Johansen H. (1979) Combined Scanning (EBIC) and Transmission Electron Microscopic Investigations of Dislocations in Semiconductors. Phys.Stat.Sol. (a)55, 611-620.

Bogdankevich O V, Borisov N A, Dyukov V G, Mityukhlyaev V B, Faifer V N, Shustov A V (1987) Electron irradiation effect on subsurface properties of cadmium sulfide single crystals. Izv.AN SSSR, ser.Fiz. 51, 437-441 (In Russian).

Bondarenko I E, Eremenko V G, Nikitenko V I, Yakimov E B (1980) The Effect of Thermal Treatment on the Electrical Activity and Mobility of Dislocations in Si. Phys.Stat.Sol. (a)60, 341-349.

Bondarenko I E, Yakimov E B, Yarykin N A (1986) The nature of the electrical activity of defects in deformed silicon crystals. Acta Phys.Polonica. A69, 393-395.

Bondarenko I E, Yakimov E B (1987) Defect investigations in deformed silicon by EBIC. Izv. AN SSSR, ser.Fiz. 51, 703-707 (In Russian).

Bondarenko I E, Panin G N, Yakimov E B (1988) Possibilities of using of EBIC for point defect distribution study. Izv. AN SSSR, ser.Fiz. 52, 1380-1382 (In Russian).

Bondarenko I E, Yakimov E B (1988) EBIC-investigation of the dislocation-impurity interaction in silicon. Solid State Phenomena. 1&2, 59-64.

Bondarenko I E, Likharev S K, Ray E I, Yakimov E B (1990) Microtomography of the semiconductor crystals in the EBIC mode. J.Crystal Growth. 103, 197-199.

Bondarenko I E, Yakimov E B (1990) EBIC Investigation of Electrical Activity of Dislocations with Different Impurity Atmospheres in Si. Phys.Stat.Sol. (a)122, 121-128.

Bresse J F (1982) Quantitative investigations in semiconductor devices by electron beam induced current mode. A Review. Scanning Electron Microsc. 1982; IV: 1487-1500.

Castaldini A, Cavallini A, Gondi P (1985) Profiles of Dislocation Images in Si by Scanning Microscopy in EBIC. Dependence on the Space Charge Cylinder Radius. Nuovo Cimento. 6D, 423-436.

Castellani L, Gondi P, Patuelli C, Berti R. (1982) On the EBIC Contrast of Dislocation in Si. Phys.Stat.Sol. (a)69, 677-685.

Cavallini A, Gondi P (1987) Space Charge Cylinder Effects on the EBIC Profiles of Dislocations. Izv. AN SSSR, ser.Fiz.. 51, 1522-1527 (In Russian).

Chi J Y, Gatos H C (1979) Determination of dopant-concentration diffusion length and lifetime variations in Silicon by scanning electron microscopy. J.Appl. Phys. 50, 3433-3440.

Dimitriadis C A (1988) Scanning electron microscopy studies of extended defects in semiconductors. Scanning Microsc. 2, 1979-1993.

Donolato C (1978) On the theory of SEM charge collection imaging of localized defects in semiconductors. Optik. 52, 19-36.

Donolato C (1979) Contrast and resolution of SEM Charge-collection images of dislocations. Appl.Phys.Lett. 34, 80-81.

Donolato C (1981) A Analytical Model of SEM and STEM Charge Collection Images of Dislocations in Thin Semiconductor Layers. I. Minority Carrier Generation, Diffusion, and Collection. Phys. Stat. Sol. (a)65, 649-658.

Donolato C (1983a) Theory of beam induced current characterization of grain boundaries in polycrystalline solar cells. J.Appl.Phys. 54, 1314-1322.

Donolato C (1983b) Quantitative evaluation of the EBIC contrast of dislocations. J.Physique, 44, C4-269 - C4-275.

Donolato C (1985a) A reciprocity theorem for charge collection. Appl. Phys.Lett. 46, 270-272.

Donolato C (1985b) Charge collection in a Schottky diode as a mixed boundary-value problem. Solid-State Electron. 28, 1143-1151.

Donolato C (1988) Recovery of semiconductor and defect properties from charge-collection measurements. Scanning Microsc. 2, 801-811.

Donolato C, Kittler M (1988) Depth profiling of the minority-carrier diffusion length in intrinsically gettered silicon by electron-beam-induced current. J.Appl.Phys. 63, 1569-1579.

Donolato C (1989) Quantitative characterization of semiconductors by EBIC. Inst.Phys.Conf.Ser. No 100, 715-724.

Eremenko V G, Nikitenko V I, Yakimov E B (1975) Concerning the mechanism of formation of the diode effect in silicon under the influence of an individual dislocation. Zh.Eksp.Teor.Fiz. 69, 990-998 (In Russian) [Sov.Phys.JETP. (1976) 42, 503-507].

Eremenko V G, Nikitenko V I, Yakimov E B (1977) The dependence of the electrical properties of silicon on the plastic deformation and annealing temperatures. Zh.Eksp.Teor.Fiz. 73, 1129-1139 (In Russian) [Sov. Phys.JETP (1978) 48, 598-603].

Eremenko V G, Nikitenko V I, Yakimov E B, Yarykin N A (1978) Donor action of dislocation in n-Si single crystals. Fiz.

tech. poluprov. 12, 273-279 (In Russian) [Sov.Phys.Semicond. 12, 157].

Everhart T E, Hoff P H (1971) Deter mination of kilovolt electron energy dissipation vs penetration distance in solid materials. J.Appl .Phys. 42, 5837-5846.

Fitting H-J, Glaefeke H, Wild W (1977) Electron Penetration and Energy Transfer in Solid Targets. Phys.Stat.Sol. (a)43, 185-190.

Frigeri C (1987) An EBIC method for the quantitative determination of dopant concentration at striations in LEC GaAs. Inst. Phys. Ser. No 87. 745-750.

Fuyuki T, Matsunami H (1981) Determination of lifetime and diffusion constant of minority carriers by a phase-shift technique using an electron-beam-induced current. J.Appl.Phys. 52, 3428-3432.

Georges A, Fournier J M, Gonchond J P, Bois D (1980) Time Resolved EBIC for quantitative analysis in p-n junctions. Scanning Electron Microsc. 1980; IV: 69-76.

Georges A, Fournier J M, Bois D (1982) Time resolved EBIC: A new destructive technique for an accurate determination of p-n junction depth. Scanning Electron Microsc. 1982; I: 147-156.

Gorlich S , Kubalek E (1985) Electron beam induced damage on passivated metal oxide semiconductor devices. Scanning Electron Microsc. 1985; I: 87-95.

Hanoka J I, Bell R O (1981) Electron-beam-induced currents in semiconductors. Ann.Rev.Mater.Sci. 11, 353-380.

Higuchi H, Tamura H (1965) Measurement of the lifetime of minority carriers in semiconductors with a SEM. Jpn J.Appl. Phys. 4, 316-317.

Holt D B, Lesniak M (1985) Recent developments in electrical microcharacterization using the charge-collection mode of the scanning electron microscope. Scanning Electron Microsc. 1985; I: 67-86.

Holt D B (1989) The Conductive Mode. SEM Microcharacterization of Semiconductors. Ed.by D.B.Holt and D.C.Joy (Academ.Press), 241-338.

Hoppe W, Kittler M (1989) On the Investigation of Dopant Boundaries in Silicon Device Structures by Means of SEM-EBIC. Cryst.Res.Technol. 24, 65-81.

Hungerford G A, Holt D B (1987). Electron dose induced variations in EBIC line scan profiles across silicon p-n-junctions. Inst. Phys. Conf. Ser. No 87, 721-726.

Ioannou D E, Davidson S M (1979) Diffusion length evaluation of boron-implanted silicon using the SEM-EBIC/Schottky diode technique J.Phys. D. 12, 1339-1344.

Ioannou D E, Dimitriadis C A (1982) A SEM-EBIC minority-carrier-diffusion length measurement technique. IEEE Trans. Electron Devices ED-29, 445-450.

Joy D C (1986) The interpretation of EBIC images using Monte Carlo simulation. J.Microscopy 143, 233-248.

Kamm J D (1976) A method for investigation of fluctuations in doping concentration and minority carrier diffusion length in semiconductors by scanning electron microscope. Solid-State Electron. 19, 921-925.

Kamm J D, Bernt H (1978) Theory of diffusion constant-, lifetime- and surface recombination velocity-measurements with the scanning electron microscope. Solid-State Electr. 21, 957-964.

Kaufmann K, Kisielowski-Kemmerich C, Heister E, Alexander H (1987) EBIC-Investigation of fresh and grown in (immobile) dislocations in GaAs. Defect Recognition and Image Processing in III-V Compounds II, ed. by E.Weber (Elsevier Sci.Publishers B.V.,Amsterdam), 163-170.

Kimerling L C, Patel J R (1979) Defect states associated with dislocations in silicon. Appl.Phys.Lett. 34, 73-75.

Kittler M (1980) On the Characterization of Electrical Active Inhomogeneities in Semiconductor Silicon by Charge Collection at Schottky Barriers Using the SEM-EBIC (II). Krist.u.Techn. 15, 575-584.

Kittler M, Seifert W (1981) On the Sensitivity of the EBIC Technique as Applied to Defect Investigations in Silicon. Phys. Stat. Sol. (a)66, 573-583.

Kittler M, Seifert W, Raith H (1989) A New Technique for the Determination of Minority-Carrier Diffusion Length by EBIC. Scanning. 11, 24-28.

Konnikov S G, Solov'ev V A, Umanskii V E, Chistyakov V M (1987) Function of generation of electron-hole pairs in III-V semiconductors under electron beam excitation. Phys. Techn. Poluprov. 21, 2028-2032 (In Russian).

Konnikov S G, Salata O V, Umanskii V E, Chistyakov V M (1990) Determination of electrophysical parameters of semiconductors in time-resolved SEM. Izv. AN SSSR, ser.Fiz. 54, 284-287 (In Russian).

Kononchuk O V, Yakimov E B (1991) Mapping of diffusion length and depletion region width in Schottky diodes. Semicond.Sci.Technol. to be published.

Koveshnikov S V, Yakimov E B, Yarykin N A, Yunkin V A (1989) Plasma Stimulated Impurity Redistribution in Silicon. Phys.Stat.Sol. (a)111, 81-88.

Koveshnikov S V, Yakimov E B, Yarykin N A, Yunkin V A (1990) Defect formation and gettering effect in plasma etched silicon. Defect control in semiconductors, ed.by K.Sumino, (North-Holland) 519-523.

Koveshnikov S V, Feklisova O V, Yakimov E B, Yarykin N A (1991) Spatial Distribution of Dislocation Related Centers in Plastically Deformed Silicon. Phys.Stat.Sol. to be published.

Kuiken H K, van Opdorp C (1985) Evaluation of diffusion length and surface recombination velocity from a planar-collection-geometry electron-beam-induced current scan. J.Appl.Phys. 57, 2077-2090.

Kveder V V, Osipyan Yu A, Schroter W, Zoth G (1982) On the Energy Spectrum of Dislocations in Silicon. Phys.Stat. Sol. (a)72, 701-714.

Leamy H J (1982) Charge Collection Scanning Electron Microscopy J.Appl. Phys. 53, R51-R80.

Luke K L, Von Roos O, Cheng L (1985) Quantification of the effects of generation volume, surface recombination velocity, and diffusion length on the electron-beam-induced current and its derivative: Determination of diffusion lengths in the low micron and submicron ranges. J.Appl. Phys. 57, 1978-1984.

Maeda K, Sato M, Kubo A, Takeuchi S. (1983) Quantitative measurements of recombination enhanced dislocation glide in gallium arsenide. J.Appl. Phys. 54, 161-168.

Marten H W, Hildebrand O (1985) EBIC profiling of bevelled samples: a precise method to determine the position of p-n junctions and doping gradients. Physica 129B, 306-311.

Menninger H, Raidt H, Gleichmann R. (1980) On the Interaction between Crystal Defects and Impurities in Silicon Investigated by Electron Microscopic Methods. Phys.Stat.Sol. (a)58, 173-180.

Mil'shtein S Kh, Nikitenko V I (1971) Investigation of local changes of silicon electrical properties under individual dislocation influence. Pis'ma Zh. Eksp.Teor.Fiz. 13, 329-332 (In Russian) [JETP Lett. 13, 233]

Milshtein S Kh, Joy D C, Ferris S D, Kimerling L C. (1984) Defect Characterization Using SEM-CCM. Relative Contrast Measurements Phys. Stat. Sol. (a)84, 363-369.

Mil'vidskii M G, Osvenskii V B, Reznik V Ya, Shershakov A N (1985) Determination of recombination activity and depth of point-like defects in semiconductor crystals by induced current technique in SEM. Fiz. tech. poluprov. 19, 38-43 (In Russian) [Sov.Phys.Semicond. 19, 22-25].

Nakamae K, Fujioka H, Ura K (1981) Measurements of deep penetration of low-energy electron into metal-oxide-semiconductor structure J.Appl. Phys. 52, 1306-1308.

Napchan E (1989) Electron and photon - matter interaction: energy dissipation and injection level. Revue Phys.Appliq. 24, C6-15 - C6-29

Niedrig H (1982) Electron backscattering from thin films. J.Appl.Phys. 53, R15-R49.

Nitz H M, Ganschow O, Kaiser U, Wiedmann L, Benninghoven A (1981) Quasi-simultaneous SIMS, AES, XPS and TDMS study of preferential sputtering, diffusion and mercury evaporation in $Cd_xHg_{1-x}Te$. Surf. Sci. 104, 365-383.

Oelgart G, Fiddicke J, Reulke R (1981) Investigation of Minority-Carrier Diffusion Lengths by Means of the Scanning Electron Microprobe (SEM). Phys. Stat.Sol. (a)66, 283-292.

van Opdorp C (1977) Methods of evaluating diffusion lengths and near-junction luminescence-efficiency profiles from SEM scans. Philips Res.Reports. 32, 192-249.

Panin G N, Yakimov E B (1989) The change of subsurface layers properties of $Cd_xHg_{1-x}Te$ under electron beam. Fiz. tech. poluprov. 23, 1351-1355 (In Russian).

Panin G N, Yakimov E B (1991) REBIC-SEM characterization of compound semiconductors. Semicond.Sci.Technol., to be published

Parsons R R, Dyment J C, Smith G (1979) Differentiated Electron Beam Induced Current (DEBIC): Quantitative Characterization of Semiconductor Heterostructure Lasers. Appl.Phys.Lett. 50, 538-540.

Pasemann L (1991) A contribution to the theory of beam induced current characterization of dislocations. J.Appl. Phys. 69, 6387-6393.

Possin G E, Kirkpatrick (1979) Electron-beam measurements of minority-carrier lifetime distributions in ion-beam-damaged silicon. J.Appl.Phys. 50, 4033-4041.

Read W T (1954) Theory of dislocation in germanium. Philos.Mag. 45, 775-796.

Reiners W, Gorlich S, Kubalek E (1985) On the primary electron energy dependence of radiation damage in passivated NMOS transistors. Inst. Phys. Conf. Ser. No 76, 507-512.

Reiners W (1990) Fundamentals of electron beam testing via capacitive coupling voltage contrast. Microelectronic Engin. 12, 325-340.

Shih C K, Friedman D J, Bertness K A, Lindau I, Spicer W E, Wilson J A (1986) Electron beam induced Hg desorption and the electronic structure of the Hg depleted surface of $Hg_{1-x}Cd_xTe$. J.Vac. Sci. Technol. A4, 1997-2001.

Shick J D (1985) Advances in electron-beam-induced-current analysis of integrated circuits. Scanning Electron Microsc. 1985; I: 55-66.

Sieber B (1989) Intrinsic or extrinsic origin of the recombination at extended defects. Rev Phys.Appliq., Colloque C6, 24, C6-47-C6-56.

Spivak G V, Saparin G V, Komolova L F (1977) The physical fundamentals of the resolution enhancement in the SEM for CL and EBIC modes. Scanning Electron Microsc. 1977; I: 191-199.

Tabet N, Tarento R-J (1989) Calculation of the electron-beam-induced current

(EBIC) at a Schottky contact and comparison with Au/n-Ge diodes. Philos.Mag.B, 59, 243-261.

Tichonov A N, Arsenin V V (1977) Solution of Ill-Posed Problems (Washington Winston/Wiley)

Van Roosbroeck W (1955) Injected Current Carrier Transport in a Semi-Infinite Semiconductor and the Determination of Surface Recombination Velocities. J.Appl. Phys. 26, 380-391.

Weber G, Dietrich S, Huhne M, Alexander H (1989) EBIC investigations of dislocations in GaAs. Inst.Phys.Conf. Ser., No 100, 749-754.

Wilshaw P R, Booker G R (1987) The theory of recombination at dislocations in silicon and an interpretation of EBIC results in terms of fundamental dislocation parameters. Izv. AN SSSR, ser.Fiz. 51, 1582-1586 (In Russian).

Wilshaw P R, Fell T S, Booker G R (1989) Recombination at Dislocations in Silicon and and Gallium Arsenide. Point and Extended Defects in Semiconductors. NATO ASI Series B, ed. by G.Benedek, A.Cavallini and W.Schroter (Plenum Press), 202, 243-256.

Wilshaw P R, Fell T S (1989) The electronic properties of dislocations in silicon. Inst.Phys.Conf.Ser. No 104, 85-96.

Wu C J, Wittry D B (1978) Investigation of minority-carrier diffusion lengths by electron bombardment of Schottky barriers. J.Appl. Phys. 49, 2827-2836.

Yacobi B G, Herrington C R, Matson R J (1984a) Decay of the electron-beam-induced current in hydrogenated amorphous silicon devices. J.Appl. Phys. 56, 557-562.

Yacobi B G, Matson R J, Herrington C R, Tsuo I S (1984b) Limitation to the application of the electron-beam-induced current in hydrogen-passivated silicon grain boundaries. J.Appl.Phys. 56, 3011-3013.

Yegorshev V V, Panin G N, Yakimov E B (1989) The effect of electron beam on the properties of compound semiconductors. Proc.12th Intern.Congress on X-ray Optics and Microanalysis, ed. by S. Jaslenska and L. J. Maksymowicz, Poland, 904-907.

Zaitsev S I, Samsonovich A V (1990) Inverse problem in electron beam diagnostics. Methods of induced concentration. Izv. AN SSSR, ser.Fiz. 54, 247-254 (In Russian).

Zaporozchenko V I, Kuleshov V F, Omel'yanovskaya N M, Pokrovskii A V (1985a) Electron-stimulated desorption of mercury from $Cd_{0.2}Hg_{0.8}Te$ surface. Poverhnost, No 4, 146-148 (In Russian).

Zaporozchenko V I, Kuleshov V F, Omel'yanovskaya N M, Pokrovskii A V (1985b) Electron-stimulated processes on $Cd_{0.2}Hg_{0.8}Te$ surface. Izv. AN SSSR, ser. Fiz. 49, 1695-1699 (In Russian).

Discussion with Reviewers

D.B.Holt: The treatment of dislocation contrast in term of combination of line charge and impurity centres is interesting. Is the theory derived in Bondarenko and Yakimov (1990)?

Author: In the paper mentioned only experimental data and some qualitative explanations of these data were presented. In my opinion, the main questions which it is necessary to take into account when the theoretical model is developed are the influence of not very high concentration of recombination centers on the recombination inside the depletion region of the Read's cylinders and the minority carrier transport along the dislocation potential relief. Up to now the knowledge about the form of potential barrier, its changes under electron beam excitation and the recombination center distribution which is necessary to solve these problems is rather poor.

D.B.Holt: Can you give a simple physical reason for believing that some dislocations are uncharged? How in your theory are they distinguished experimentally?

Author: The thermal treatment of dislocations can change their energy spectrum and therefore it can lead to the dislocation charge change. For example, in Cz-Si decrease of the dislocation charge during annealing is associated with the shallow donor formation near dislocations (Bondarenko et al, 1980). The other possibility can be the interaction between impurities and intrinsic dislocation centers which can change the electrical activity of both. The dislocation charge can be controlled by the experiments using a microcontact to the dislocation (Eremenko et al, 1975) or by remote contact EBIC (REBIC) measurements. Some information about the dislocation charge can be obtained also by such macroscopic techniques as Hall effect or C-V measurements but in this case the problem is to separate dislocation effects from the influence of point defects which can be created during the plastic deformation.

D.B.Holt: The idea of electron beam tomography is an attractive one but is it practical? That is to say, can the amount of careful measurement and detailed computation be reduced to a level at which the method will be widely used? Would it be feasible to develop a tomography program for EBIC that could be included as an option to be selected from an operating menu on an image processor in the foreseeable future, for example?

Author: In my opinion, in near future it will be possible to use electron beam tomography programs as a conventional software for EBIC image processing. For this purpose it is necessary to improve the measurement accuracy which can be achieved using modulation techniques or by the development of effective programs for image filtration. The other question is the development of effective models and programs for the three-dimensional reconstruction. In the case when diffusion length is changed only in depth some reconstruction procedures have been already proposed (see e.g., Donolato (1989)).

M.Kittler: The electron range R is an important parameter to calculate the generation function, for example. To get R as a function of beam energy E_b you used for Si the following relation - $R = 0.0171\ E_b^{1.75}$ - which based on the work of Everhart and Hoff. However, taking Fig. 4 of Leamy`s work [J. Appl. Phys. 53, R 51 (1982)] which is attributed to Everhart and Hoff, too, one obtains R values being about 1.5 times large. Is the relation used in your work more precisely and if yes, why?
Author: The dependence of the EBIC signal on R is very complex therefore it is not so easy to reveal the R value from the EBIC measurements. Moreover, EBIC is not very sensitive to the form of the generation function in the crystals with not very small diffusion length. But in any case it is possible to check the possibility of using the particular expression for $G(\bar{r})$ and R by measurements of the well characterized samples. We do not measure the R value but the R and $G(\bar{r})$ expressions used in our investigations for the W calculation were checked by the characterization of the same samples by C-V technique. We obtained the good correlation between the results obtained by these two techniques.

M.Kittler: You are studying contrast values C of dislocations in dependence on beam current I_b. Decreasing I_b the noise increases and consequently the accuracy of measured C-values reduced. How accurate are your C_{min}-values measured at $I_b \sim$ 1 pA, which you use for normalization in Fig. 2b?
Author: In the case of small I_b to decrease the noise we increased the the time of measurements but in any case Fig.2b should be considered only as a qualitative one. In my opinion, this Fig. helps to reveal some characteristic features of the $C(I_b)$ dependences, e.g., the dependence of the EBIC contrast stability under e-beam excitation on the impurity atmosphere state.

M.Kittler: You discuss the important role of impurity atmosphere for EBIC contrast. Furthermore you evaluate the concentration of recombination centers near a dislocation to be about 10^{18}- 10^{19} cm^{-3}. Recombination-active point defects as transition metals in Si are supersaturated in such a concentration and will form precipitates. Indeed, metal precipitates were found as main sources of strong EBIC contrast of grain boundaries [see J.L.Maurice, C.Colliex, Appl.Phys.Lett. 55, 241 (1989)] and of dislocations (see D.M.Lee et al, Semiconductor Silicon 1990, ed. by H.R.Huff, K.G.Barraclough, J.Chikava, p. 638). So it seems that silicide precipitates will have a more pronounced influence on EBIC contrast as atmospheres of solute impurities, especially when strong contrasts are found. Does your results confirm this hypothesis?
Author: Of course, transition metal precipitates can strongly increase the dislocation EBIC contrast. It was observed in the papers mentioned by you and in our experiments on Si doped with gold (Aristov et al, 1987). But it seems to me that in the case discussed in the chapter 5.2 it is possible to ascribe the EBIC contrast increase to an oxygen because this increase was observed only in Cz-Si and in Fz-Si deformed and annealed in the same conditions the contrast did not exceed 1-2% if these crystals were not specially doped by gold. Of course, oxygen atoms probably form some precipitates in dislocation atmospheres.

Discussion with Reviewers continued on page 80.

Additional Discussion with Reviewers of the paper "Electron Beam Current Investigations of Electrical Inhomogeneities with High Spatial Resolution" by E. Yakimov, continued from page 96.

L.J.Balk: Applications of phonon focusing tomography have shown that a useful result can only be achieved for crystals with small number of defects. An EBIC-tomography would be even more complicated in terms of interpretability. What would be the typical material problems you would believe can be solved by means of such a technique?

Author: It seems that in near future it will be possible to reconstruct the L three-dimensional distribution using e-beam tomography. But for defects situated at distances smaller than a mean L value it is very difficult to resolve them by such procedure. From this point of view you are right and this technique is more suitable for low defect density. But in some cases, e.g., for defects with very high recombination activity or in crystals with low L values, it is possible to achieve high spatial resolution. Thus, the most promising fields of material science for e-beam tomography applications are defect distribution reconstruction in crystals with low defect density and investigations of point defect distribution near extended defects with high recombination activity and using these results for studying of interaction between these defects.

L.J.Balk: In our work on EBIC investigation we found that the electron beam significantly modifies the electric potentials within a GaAs-MESFET (presented at the 3rd European Conference on Electron and Optical Beam Testing, Como, Italy). Can you comment, to what extent such changes within the collecting electrical barrier deteriorate the quantification of the results achieved?

Author: The electron beam influence on the properties of the structure under investigation is very important problem because to improve a spatial resolution it is necessary to increase measuring time and as a result to change properties of the structures under investigation. These changes, of course, prevent the quantitative measurements. In your case the potential barrier changes should be smaller than the measurement accuracy, e.g., in the case of dI_c/dW measurements smaller than the amplitude of the ac voltage applied to the structure. In other cases, these changes will influence the accuracy of results obtained and therefore they should be taken into account.

C. Donolato: You determine a diffusion length depth profile L(z) from collection efficiency measurements $\eta(E_b)$ on a Schottky diode by assuming a model function for L(z) containing 4 unknown parameters; the depletion width W is probably an additional one. The experimental data to be fitted (Fig. 1) consist of 13 measurements. Could you give an idea of the error by which the estimates of the unknown parameters are affected?

Author: When we obtained diffusion length depth profile on plasma etched samples as a rule we etched only part of the crystal. Therefore we can carry out the experiments on the both etched and untreated Si with the same metal thickness and by fitting the dependence of η on E_b for the untreated part of the sample we can obtain a metal thickness t_m, depletion region width W and the value of $1/L_0^2 + 1/L_{Au}^2$. Moreover, from the C-V measurements we obtained that plasma etching do not change W. Therefore, we need to obtain only two parameters. In this case the difference between the values of parameters B and z_0 in L(z) dependence obtained from EBIC measurements and those calculated using the data of DLTS measurements does not exceed 10%. If it is impossible to obtained the W value from additional measurements to increase the number of equations it is possible to carry out the measurements at different applied bias and to use the known dependence of W on an applied voltage U $W = (\varepsilon\varepsilon_0 U/eN_d)^{1/2}$, where ε is the dielectric constant. But in any case if L(z) dependence can be presented in a parametric form the reconstruction procedure is less sensitive to the measurement accuracy than in the cases when L(z) dependence is unknown.