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► To cite this version:

E. Yakimov. NEW POSSIBILITIES OF EBIC FOR DISLOCATION STUDY. Journal de Physique IV Proceedings, 1991, 01 (C6), pp.C6-193-C6-198. 10.1051/jp4:1991629 . jpa-00250715

HAL Id: jpa-00250715

<https://hal.science/jpa-00250715>

Submitted on 1 Jan 1991

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NEW POSSIBILITIES OF EBIC FOR DISLOCATION STUDY

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Abstract The recent results of the EBIC investigations of dislocations in Si demonstrating the influence of point defect atmospheres on the characteristics of the EBIC contrast of the both charged and uncharged dislocations are discussed. It is shown that from such investigations characteristics of these atmospheres can be obtained.

1. Introduction

Dislocations are one-dimensional defects and it was usually believed that their dimensions in the direction perpendicular to the dislocation line are much smaller than a dimension of a region of electron-hole generation by a focused electron beam. To calculate the EBIC contrast of uncharge dislocations Donolato [1-3] proposed the model in which dislocation recombination properties were described by recombination strength $\lambda = \pi \rho_d^2 / \tau_d$ 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 ρ_d is very small and it is impossible to obtain its value from EBIC measurements. But even if all of the dislocation centers are situated in its core they can capture majority carriers what leads to the space charge cylinder formation around dislocations. In this case ρ_d has an obvious physical sense and is equal to the value calculated by Read [4] with $\tau_d \approx 0$ inside this cylinder [5]. The EBIC contrast of charge dislocations was discussed in [6,7] where the contrast value was assumed to be proportional to the dislocation barrier height. Unfortunately the both models do not take into account dislocation point defect atmospheres formed near the dislocations in real crystals. Nevertheless, the influence of such atmospheres on the dislocation EBIC contrast was discussed in [8-14] and therefore the question arises about the possibility to obtain the characteristics of these atmospheres from the EBIC measurements. To solve this problem the EBIC investigations of charged and uncharged dislocations in Si introduced at a low enough temperature, the impurity atmosphere of which was controlled by the subsequent thermal treatment and the crystal impurity content, were carried out [14]. On the base of these results the possibilities of impurity atmosphere studies by EBIC are

discussed in the present paper.

2. Dislocation characterization

To understand the mechanisms of the impurity atmosphere effect on the dislocation EBIC contrast it is necessary to study the well characterized dislocations. For this purpose the individual 60-degree dislocations approximately perpendicular to the surface introduced at 600° by four point bending were studied [14]. To change the impurity atmosphere state and dislocation charge subsequent thermal annealing of the crystals with different impurity contents were used. The impurity atmosphere state was controlled by measurements of starting stresses which were very sensitive to the existence of impurity complexes formed near the dislocation [15]. To control the dislocation charge in accordance with [16,17] the contrast dependence on the beam current was measured and the results of I-V characteristic measurements on microcontacts to dislocation etch pits [18] were used. It has been shown that dislocations introduced by the plastic deformation in the temperature range from 600 to 700°C are charged and space charge cylinders are formed around these dislocations. After annealing at $T \geq 850^\circ\text{C}$ 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%.

3. Investigations of uncharged dislocations in Si

The dependence of the EBIC contrast C of uncharge dislocations on electron beam current is relatively weak (Fig.1, curve 5) and differs from that observed on dislocations with a potential barrier (Fig.1, curves 1-4). It was found [14] that for such dislocations the

Fig.1. a- Dependence of the EBIC contrast on beam current for dislocations after 600°C deformation (1-4, curve 3 for quenched sample) and subsequent 900°C 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 [14]. 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 the every curve beam currents.

derivative $dC/dW = (dC/dU)dU/dW$ is a curve with a maximum which

correlates well with the depth distribution of e-h generation $h(z)$ up to a depth $z \sim 1.8 \mu\text{m}$ (Fig.2). The coincidence of the $h(z)$ and dC/dW curves is an evidence that the diffusion length L_D is very small near

Fig.2. Derivative of the contrast versus depth for an annealed dislocation in Si (1). 2- depth distribution of the generation function $h(z)$ [14].

the dislocation. Evaluations made on the base of Donolato's model under the assumption that the difference between dC/dW and $h(z/R)$ is determined by the fact that at $z > 1.8 \mu\text{m}$ a fraction of the minority carriers is generated outside the cylinder with radius ρ_D gives for the radius $\rho_D \sim 1 \mu\text{m}$ and for the diffusion length $L_D \sim 0.1 \mu\text{m}$ [14]. 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 $10^{18} - 10^{19} \text{ cm}^{-3}$, i.e. about $10^9 - 10^{10}$ centers per cm along the dislocation line. This value is in good agreement with the oxygen concentration gathered by a dislocation what obtained from the investigations of dislocation donor center formation [15]. Of course, the parameters of the dislocation impurity atmosphere were obtained under assumption that inside the defect cylinder $\tau_d = \text{const}$. Under any other assumptions about the dependence of τ_d on ρ some other values would be obtained. It should be also mentioned that a nonmonotonous dependence of the contrast value on beam current can evidences that two or more different recombination centers are formed in dislocation impurity atmospheres and these centers have different dependence of capture cross section on an excitation level. For example, in n-type crystals for donor centers with energy level situated above the Fermi level the capture cross section of minority carries can increase when these centers capture the majority carriers. Thus, this method based on the measurements of I_c and dI_c/dW as well as that proposed in [19] gives a possibility to obtain the parameters of the impurity atmosphere but 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.

4. Properties of charged dislocations in Si

The dependences of the dislocation contrast on beam current I_b in the samples with different impurity contents are shown in Fig.1. In accordance with [16,17] the decrease of the contrast with increasing beam current is observed. It should be stressed the difference between curves 3 and 4 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 [15] the difference observed shows that dislocation contrast is associated with such complexes.

It is easily seen from Fig.1 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 in accordance with Wilshaw theory [6,7]. 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 [20] 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 as well as the I_b value at which the contrast begins to decrease with increasing I_b essentially depends on the state of the dislocation point defect atmosphere at practically unaltered barrier height. These results contradict Wilshaw model of the EBIC contrast for charged dislocations [6,7] because in this model the dislocations with equal barrier height in the crystals with the same doping level must have the same contrast. To explain this contradiction it was taken into account [14] that besides the centers with energy level situated at 0.44 eV from the valence band [21], a set of other energy levels was observed in plastically deformed Si [11,22]. Under electron beam excitation the dislocation barrier height is equal to

$$\varphi = \frac{kT}{e} \ln \frac{c_e N_D (1-f) N_d}{c_e N_D f N_C \exp(-\Delta E/kT) + k_1 I_b}$$

where f is the filling factor of dislocation states, N_d is the shallow donor concentration, c_e is the probability of electron capture on the dislocation state, N_D is the density of centers along dislocations in its core, N_C is the energy state density in conduction band, ΔE is the depth of the dislocation energy level, I_p is the hole flow to the dislocation $I_p = k_1 I_b$. It was assumed that some of 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. Thus, 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, i.e. the coefficient k_1 , 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 near the edge of the Read's cylinders. In this model it is necessary to assume that near the edge of Read's cylinder the recombination center concentration is about $10^{17}-10^{18} \text{ cm}^{-3}$, as in the case of dislocations annealed at higher temperatures. But the recent DLTS data [23] show that the concentration of deep level centers in this region is much lower. It was also shown that the concentration of deep level centers in the impurity atmosphere can be equal to the dopant concentration at a distance about some μm what leads to the formation of a plateau of electrostatic barrier near the dislocation core in Si. This gives an additional 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 radius 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 this critical value of I_b 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. This process can be not very fast because inside the potential barrier plateau the electric field is very small. 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. In the frame of this assumption it is possible to obtain Read radius value and the dimensions of the potential barrier plateau from the dependence of the EBIC contrast on beam current, i.e. to evaluate the deep level concentration at the edge of this plateau. Moreover, from the measurements of dI_c/dW value for charged dislocations it is possible to obtain some knowledge about the minority carrier diffusion along the dislocation perpendicular to the surface to the Schottky barrier and about the influence of such dislocations on a local depletion region width.

5. Conclusion

The results of recent EBIC and DLTS investigations show that impurity atmosphere have dimensions up to some μm for the both charged and uncharged dislocations. This atmosphere determines some peculiarities of the dislocation EBIC contrast which gives the possibilities to obtain the characteristics of dislocation atmosphere from EBIC measurements. But to do this it is necessary to develop theoretical models describing the influence the impurity atmosphere on the dislocation recombination properties. Some features of such models were discussed in the present paper. It was shown that under some assumption about the law of recombination center distribution around a dislocation it is possible to obtain characteristics of this distribution for uncharged dislocations. For charged dislocations it is necessary to take into account their influence on the Schottky barrier depletion region width and a recombination inside Read's cylinder through the recombination centers situated in the impurity atmosphere. To clarify the main features of models describing the dislocation EBIC contrast in real crystals additional experiments are necessary.

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