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Résumé. — Dans certains articles récents, les mesures par Ourmazd *et al.* (*J. Physique Colloq.* **44** (1983) C4-289) de la variation en fonction de la température du contraste des images obtenues par EBIC des dislocations dans le silicium ont été interprétées comme contredisant les prédictions du modèle de contraste linéaire que nous avions proposé. Nous montrons ici que cette conclusion était basée sur une hypothèse incorrecte concernant la forme fonctionnelle de la force de recombinaison de la dislocation.

Abstract. — In some recent papers the measurements by Ourmazd *et al.* (*J. Physique Colloq.* **44** (1983) C4-289) of the temperature dependence of the electron beam induced current contrast of dislocations in silicon have been interpreted as being in disagreement with the predictions of the linear contrast model proposed by Donolato. Here it is shown that this conclusion was based on an improper assumption regarding the functional form of the recombination strength of a dislocation; omitting this assumption removes the discrepancy.

The electron beam induced current (EBIC) technique of the scanning electron microscope (SEM) has proved to be a useful tool for investigating recombination effects at single defects in semiconductors [1]. EBIC observations are usually made at room temperature; however, investigation of the EBIC contrast as a function of the temperature offers, at least in principle, the possibility of a more detailed characterization of the recombination process at defects.

Recently, Ourmazd *et al.* [2] presented determinations of the temperature dependence of the EBIC contrast of individual dislocations in silicon; by analysing their results they concluded that the contrast model proposed by Donolato [3, 4] was unable to describe the observed temperature-dependent properties of the contrast. To explain the data, Ourmazd *et al.* suggested a modification of the theory consisting in assuming a different minority-carrier diffusion length at points far from and close to the dislocation. The conclusion of Ourmazd *et al.* seems to have been accepted in subsequent theoretical studies on the subject [5, 6], where the results of reference [2] were explained by a non-linear dependence of the contrast on the recombination strength of a dislocation.

The aim of this communication is to show that the disagreement between the data of reference [2] and the linear contrast model [3] actually does not exist, and is only a consequence of the introduction of a hypothesis, which is extraneous to that model.

Let us summarize the essential features of the results of Ourmazd *et al.* :

(a) In the examined temperature range the contrast is a linear increasing function $c(T)$ of the temperature.

(b) The normalized (linear) function $c(T)/c(T_0)$, where T_0 is a given temperature, is different for different dislocations of the same kind.

(c) From (a) and (b) it follows that the derivative of the contrast with respect to the temperature $\mathrm{d}c(T)/\mathrm{d}T$ of different dislocations has a constant value m_i, which however is dependent on the dislocation (labelled with an index i) being considered. It was found that the values m_i can be related to the corresponding values of the room-temperature contrast $c_i(T_0)$ through an equation of the form

$$m_i = \alpha c_i(T_0) + \beta , \tag{1}$$

where α and β are constants independent of i.

When applied to dislocations, Donolato's model yields an expression for the related EBIC contrast of the form [4]

$$c = \gamma F[R(E), L, \text{geometry}] , \tag{2}$$

where γ [$\mathrm{cm}^2.\mathrm{s}^{-1}$] is the recombination strength (or line recombination velocity) of the dislocation, $R(E)$ is the energy-dependent range of the electrons of the SEM beam, and L is the bulk diffusion length. In equation (2) the term « geometry » indicates the set of parameters describing the sample-dislocation configuration. Equation (2) also shows that the contrast model is linear, since c and γ are related linearly.

In the experiments of reference [2], L was found to be independent of T, hence F is temperature-independent as well; thus the temperature dependence only appears in γ. To include the possibility that dislocations of the same character contain a different concentration λ of recombination centres [2], the recombination strength should be written as a function $\gamma(\lambda, T)$. Thus equation (2) gives for the i-th dislocation of the group

$$c_i(T) = \gamma(\lambda_i, T)\, F_i\,, \qquad (3)$$

where the F_i's are temperature-independent, but are in general different, since the dislocations could have been at different depths.

According to equation (3), the linearity of the functions $c_i(T)$ (see result (a)) can be explained by assuming a linear dependence of γ upon T; an explicit expression will be given shortly.

The interpretation of the result (b) requires the evaluation of the ratio $c_i(T)/c_i(T_0)$; use of equation (3) yields

$$\frac{c_i(T)}{c_i(T_0)} = \frac{\gamma(\lambda_i, T)}{\gamma(\lambda_i, T_0)}\,. \qquad (4)$$

At this point Ourmazd *et al.* essentially suppose γ to have the form

$$\gamma(\lambda, T) = \lambda\varphi(T)\,. \qquad (5)$$

With this assumption, equation (4) gives

$$\frac{c_i(T)}{c_i(T_0)} = \frac{\varphi(T)}{\varphi(T_0)}\,, \qquad (6)$$

since the factor λ_i cancels out. Equation (6) foresees that the normalized contrast should be a unique function of the temperature for all dislocations of the group, since the right-hand side of equation (6) does not depend on the index i. This prevision disagrees with the result (b). However, the disagreement is only a consequence of the hypothesis (5); without this assumption the normalized contrast of equation (4) will in general be dependent on the index i, i.e. be different for different dislocations.

To discuss the result (c), it is sufficient to take the derivative of equation (4); by recalling that experimentally $\mathrm{d}c_i(T)/\mathrm{d}T$ was found to have a constant value m_i, we obtain

$$\frac{m_i}{c_i(T_0)} = \frac{1}{\gamma(\lambda_i, T_0)}\,\frac{\mathrm{d}\gamma(\lambda_i, T)}{\mathrm{d}T}\,. \qquad (7)$$

This relation entails that $\mathrm{d}\gamma/\mathrm{d}T$ should be constant as well; hence γ must have the form

$$\gamma(\lambda, T) = \gamma(\lambda, T_0)\,[1 + \varepsilon(\lambda)\,(T - T_0)]\,. \qquad (8)$$

Thus equation (7) becomes

$$\frac{m_i}{c_i(T_0)} = \varepsilon(\lambda_i)\,. \qquad (9)$$

The experimental fit (1) yields for this ratio

$$\frac{m_i}{c_i(T_0)} = \alpha + \frac{\beta}{c_i(T_0)}\,. \qquad (10)$$

Equation (10) expresses in particular that the ratio $m_i/c_i(T_0)$ is different for different dislocations; obviously this property can be accounted for through the function $\varepsilon(\lambda)$ of equation (9), whose values $\varepsilon(\lambda_i)$ will in general be different. On the contrary, it is easy to check that if $\gamma(\lambda, T)$ is supposed to have the property (5), the ratio of equation (9) would be the same for all dislocations, in contradiction with the experimental result (10). The empirical relation (10) (or (1)) between m_i and $c_i(T_0)$, however, does not provide a direct connection between $\varepsilon(\lambda)$ and $\gamma(\lambda, T_0)$, since the equality following from equations (9), (10) with the aid of equation (3)

$$\varepsilon(\lambda_i) = \alpha + \frac{\beta}{\gamma(\lambda_i, T_0)\, F_i} \qquad (11)$$

involves additionally the geometrical factor F_i.

In the attempt of overcoming these apparent discrepancies, different interpretations have been proposed [2, 5, 6], which, however, seem to have generally the drawback of introducing some *ad hoc* hypothesis, in order to explain that specific experiment. Thus, for instance, a space-varying diffusion length is assumed by Ourmazd *et al.* [2], without further evidence for this inhomogeneity. Pasemann [5] assumes a ratio of ten between the depths of two dislocations, to explain the related $c(T)$ plots, although in reference [2] the depths had not been evaluated. Jakubowicz [6] makes the opposite assumption that all observed dislocations had the same depth.

It seems then clear that the knowledge of the dislocation depth is essential for a definite interpretation of the experiments. In the framework of the approach suggested here, this knowledge would allow the evaluation of the geometrical factors F_i; thus the experimental values $c_i(T_0)$, m_i and equations (3), (9) would assign the values of the functions $\gamma(\lambda, T_0)$ and $\varepsilon(\lambda)$ at $\lambda = \lambda_i$. However, since the concentrations of recombination centres λ_i are not known, the form of these functions and hence that of γ would still remain largely arbitrary. In any case, it should be remembered that the expression (8) for $\gamma(\lambda, T)$ only gives an empirical description of the measurements and as such should be substantiated by a physical model of the recombination process.

The main advantage of the interpretation suggested here is that the three-dimensional and linear character of the contrast model of equation (2) is preserved. This model could explain satisfactorily the room-temperature EBIC images of different defects [7] by considering γ only as a phenomenological parameter. To describe the temperature-dependent behaviour of the contrast, it is sufficient to allow γ to become a suitable function of the temperature and density of recombination centres, while keeping the geometrical features of the model unchanged. In the present case of dislocations, however, the specification of γ cannot probably be unique, as quite different trends of $c(T)$ have been observed in similar temperature ranges [2, 8].

References

[1] Leamy, H. J., *J. Appl. Phys.* **53** (1982) R51.

[2] Ourmazd, A., Wilshaw, P. R. and Booker, G. R., *J. Physique Colloq.* **44** (1983) C4-289.

[3] Donolato, C., *Optik* **52** (1978/79) 19.

[4] Donolato, C., *J. Physique Colloq.* **44** (1983) C4-269.

[5] Pasemann, L., *Phys. Status Solidi* (a) **84** (1984) 133.

[6] Jakubowicz, A., *J. Appl. Phys.* **57** (1985) 1194.

[7] Donolato, C. and Klann, H., *J. Appl. Phys.* **51** (1980) 1624.

[8] Ourmazd, A. and Booker, G. R., *Phys. Status Solidi* (a) **55** (1979) 771.