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Evaluation of the PhD thesis

„Enhanced charge carrier thermoemission from the dislocation-related electronic states in silicon“

submitted by

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Dislocations in semiconductors are frequently formed during crystal growth as a result of mechanical stress. They have been typically related to device failures due to their effect on various semiconductor properties such as excess carrier lifetime, junction currents, etc. In addition, their strong interaction with impurities – in particular fast diffusing metal impurities – produces many problems in silicon device fabrication. Besides such detrimental effects, dislocations may also be viewed as nanoscopic systems embedded in a semiconducting material. Ideally, they form one-dimensional quantum-wire-like electronic systems which have interesting electronic and optical properties. The latter are mainly related to defect-specific luminescence which can potentially be used as the basis for infrared light emitters. Dislocation networks (DN) have gained special attention in recent years since they provide a somewhat well-defined model system which allows studying relevant properties of dislocations. Such networks can be found in typical small-angle grain boundaries found in polycrystalline materials, but can also be produced in a controlled way using techniques of wafer bonding, which furthermore opens the route to use DNs as part of silicon devices.
Maxim Trushin's thesis tackles an important problem of dislocations in silicon, i.e. thermal emission of charge carriers from dislocation-related deep level. He makes use of the special geometry related to DNs produced by wafer bonding which are located in a fixed depth inside the space charge layer of a Schottky contact. Experiments and model calculations provide a consistent and novel insight into enhanced charge carrier emission. Maxim Trushin's thesis presents novel scientific results by a careful and systematic analysis based on existing literature and going well beyond current understanding. It is written in a

clear and well organized way and relates the results to pre-existing data and models in a fully adequate way. References listed in the bibliography are well chosen in the sense that important papers are referred to without citing the vast amount on literature in the broader environment of the thesis' topic.

The thesis is organized into four chapters. Chapter 1 provides an **introduction** into the topic with motivation and a short but suitable overview of previous studies on dislocations in silicon and in particular dislocations networks.

Maxim Trushin presents a thorough **theoretical analysis** of field-enhanced thermal emission of charge carriers from dislocation-related states in Chapter 2. The main ingredients of the treatment are (i) the deformation potential of the dislocation, (ii) the electric field due to the dislocation charge, and (iii) the external field of the junction. The equations are numerically evaluated and Poole-Frenkel coefficients are calculated for 60° and screw dislocations.

Experimental results are presented in Chapter 3. Experimental techniques include standard CV- and IV-curves with deep level transient spectroscopy, DLTS, as the main tool. Maxim Trushin uses standard DLTS as well as variants for special purposes. Besides deep levels detected by DLTS, shallow states in n- and p-type material are observed which can be attributed to one-dimensional bands resulting from the dislocation strain field. Most probably, the special geometry with dislocation lines parallel to the Schottky junction is the reason for the clear signal obtained in this work, since carriers captured to the bands are likely to vanish by transport along the dislocation rather than thermal emission. Special focus is on the field- and charge-dependence of the related DLTS signals in order to compare to the model developed in Chapter 2. In all cases, a good agreement of experimental and theoretical results is obtained.

Summary and conclusion are provided in Chapter 4 in a concise way.

Maxim Trushin has considerably contributed to scientific progress as reflected by his publications combined in this thesis (see papers PI-PIV) and also his additional work listed as AI to AXII where he is the first author in 8 cases. He is highly visible in the community as a participant of international conferences and I should mention here that he will present his results as an invited speaker on the 17th International Conference on Extended Defects in Semiconductors, EDS-2014, which will be held form Sept. 14 to 19 in Göttingen, Germany.

The Ph.D. thesis written and submitted by Maxim Trushin can be accepted and the doctoral degree can be awarded to the author after a successful defense.

(Prof. Dr. Michael Seibt) Göttingen, June 17th, 2014

Q1: Hedemann and Schröter (Ref. 31) show DLTS simulations of electric field-enhanced thermal emission from nickel silicide platelets in silicon with a rather small effect on DLT spectra compared to the case discussed here. What is the main difference between that situation and the DNs treated in this thesis?

Q2: You nicely show the combined action of the potentials due to the dislocation strain field, the line charge and the external field. During the DLTS emission phase the dislocation line charge will change as a result of carrier emission, i.e. the barrier lowering will be time-dependent. How could you take into account this time dependence?

Q3: You present impressive data on one-dimensional bands in n- and p-type material. The band-like character implies carrier mobility along the dislocations. In the DNs the one-dimensional character may be disturbed by intersecting dislocations. Do you see any hint for some localization and how would it show up in your experiments.