свидетельствовать об эмоциональном возбуждении, о тревожном состоянии, об усталости, алкогольном или посталкогольном состоянии.

Заключение. АПК УПДК-МК позволяет оценить и осуществить коррекцию функциональной надежности водителей автотранспортных средств. Разработана векторная математическая модель оценки функциональной надежности водителей на основе анализа многомерного пространства психофизиологических характеристик. Таким образом, использование современных информационных психодиагностических технологий позволяет проектировать перспективные инструментальные способы тренинговой оптимизации функциональной надежности и эффективность деятельности труда водителей автотранспортных средств.

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CALIBRATION FACTORS FOR THE DETERMINATION OF RADIATION-INDUCED OXYGEN-VACANCY COMPLEXES AND OXYGEN DIMER CONCENTRATIONS IN SILICON CRYSTALS BY INFRARED ABSORPTION

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Combined electrical (Hall effect) and optical (Infrared absorption) studies of similar silicon crystals irradiated with fast electrons have been carried out. On the base of analysis of the data obtained the calibration factors for the determination of concentrations of the radiation-induced oxygen-vacancy complexes in silicon crystals by infrared absorption are deduced. The calibration coefficient for the determination of the oxygen dimer concentration is estimated as well.

Oxygen is one of the most abundant and technologically important impurities in silicon. In as-grown Si crystals oxygen is mainly present in the form of interstitial (O_i) atoms. The O_i concentrations are usually determined from room temperature (RT) measurements of the intensity of the infrared (IR) absorption band at 1107 cm^{-1} [1]: $[O_i] = 3.14\times10^{17}\times\alpha_{1107}$ cm^{-3} [2]. Although Oi atoms in Si are electrically neutral and immobile at RT, they contribute to formation of a large variety of oxygen-related radiation- and thermally-induced defects [1, 3]. All these centers give rise to local vibrational modes [1] and Fourier-transform infrared spectroscopy (FTIR) has been successfully used in the studies of many oxygen-related aggregates including vacancy-oxygen complexes VO_n ($n \geq 1$) [4] and oxygen dimer (O_{2i}) [5]. Among the above mentioned defects only VO (A-center) in n-type S_i and VO_2 complex (in a metastable state [6]) can be detected by electrical measurements. On the other hand, absorption lines due to all of these defects can be observed in FTIR absorption spectra. In many cases it is important to know the absolute values of defect concentrations. However, the available information on calibration coefficients for the determination of the VOn (n = 1-4) and O_{2i} concentrations by IR absorption is very limited [7, 8].

In 1986 Oates and Newman [9] determined the calibration coefficient for the VO absorption peak at 830 cm^{-1} (measurements at room temperature). According to their work, [VO] =

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$6.1\times10^{16}\times\alpha_{830}$ cm^{-3}, where α_{830} is an amplitude of the vibrational absorption band at 830 cm^{-1}. Oxygen-rich Si samples doped with tin and irradiated with 2 MeV electrons at RT were studied in the work. After the irradiation the main vacancy-related defects were SnV complexes. Upon further annealing at about 160 °C these complexes started to dissociate and the released vacancies were captured by Oi atoms to form VO defects. The concentration of removed Oi was measured and assumed to be equal to the concentration of generated VO. Such procedure seems to be rather reliable. A very similar calibration factor for determination of the VO concentration in Si was obtained also by Davies et al. [7] in their work on modeling the generation kinetics of radiation-induced defects. However, in both cases [7, 9] the IR absorption measurements were carried out with a rather low spectral resolution, the measured full width at half of maximum (FWHM) of the 830 cm-1 band was about 9 cm-1 in the spectra presented. The actual FWHM of this band in the spectra measured at RT is less than 6 cm^{-1} (of about 5.6 cm^{-1} [10]) and to get a correct value of the absorption coefficient of the band (α_{830}), measurements with a higher resolution are required.

In the present work we have used two similar sets of oxygen-rich (Czochralski-grown) phosphorus-doped n-type Si crystals with a resistivity of about 1 Ω cm. Both sets were irradiated with 6 MeV electrons at RT with the same doses in the range of $(1\text{-}5)\times10^{16}$ cm^{-2}. The VO concentration (concentration of the defect with EC – 0.18 eV level) in one set of samples was determined by an analysis of the temperature dependences of free carriers obtained by means of the Hall effect measurements in the temperature range 77-400 K. Another set of samples was used for FTIR absorption measurements, which were carried out in the wavenumber range 400-4000 cm^{-1} at low temperatures (LT, ≤20 K) with a spectral resolution of 0.5 cm-1 and at RT with a spectral resolution of 1 cm-1.

The absorption bands related to VO in the neutral charge state (at 830 and 836 cm^{-1} in the spectra measured at room temperature and low temperature, respectively) as well as in the negative charge state (at 877 and 885 cm^{-1} in the RT and LT spectra, respectively [1]) were detected (Fig.1).

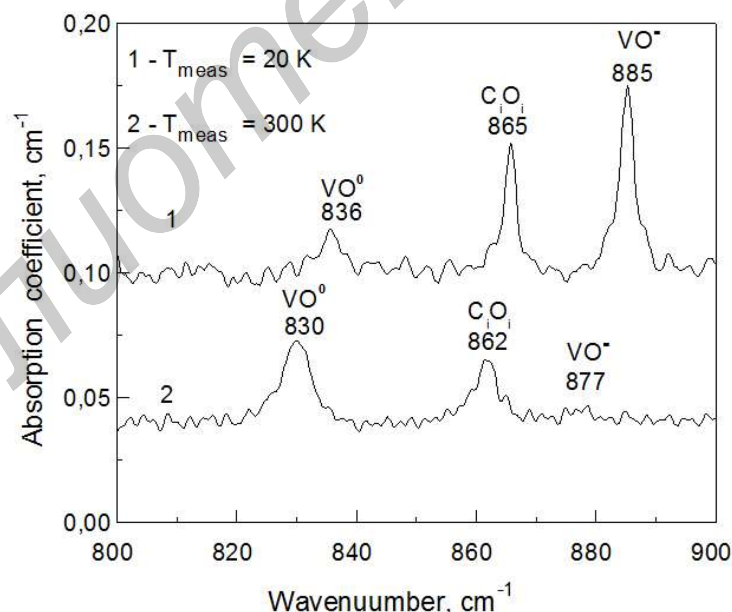

Fig. 1. Fragments of absorption spectra measured at 20 K (1) and at room temperature (2) for a Cz-Si sample ($[O_i] = 1.0\times10^{18}$, $[C_s] = 2\times10^{16}$, $[P] = 5\times10^{15}$ cm^{-3}) irradiated with 6 MeV electrons to a dose of 1.3×10^{16} cm^{-2}.

The combined analysis of the electrical and optical data obtained has allowed us to deduce the following calibration for the determination of the VO concentrations in silicon by IR absorption: RT measurements - $[VO] = 8.5\times10^{16}\times(\alpha_{830} + \alpha_{877})$ cm^{-3}, LT measurements (<20K) –

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[VO] = $3.5\times10^{16}\times(\alpha_{836} + \alpha_{885})$ cm^{-3}. We have estimated also the calibration coefficients for the VO integrated absorption.

Based on the calibration data obtained for the VO center and assuming that the oscillator strength of the oxygen atom vibrations as well as the shape of an appropriate band are the same for the O atoms located in the vacancy site with different enviroments we have also estimated calibration factors for a determination of the VO_2 (band at 895 cm^{-1}), VO_3 (bands at 910 and 975 cm^{-1}), VO_4 (band at 991 cm^{-1}), V_2O (band at 833.4 cm^{-1}) and V_3O (band at 842.4 cm^{-1} [10]) concentrations in silicon by infrared absorption measurements at low temperatures. The concentrations of the above mentioned complexes can be determined as: [VO2] = 4.25×1016×α_{895} cm^{-3}, [VO_3] = $8.5\times10^{16}\times(\alpha_{910} + \alpha_{975})/2$ cm-3, [VO_4] = $4.25\times10^{16}\times\alpha_{991}$ cm^{-3}, [V2O] = $8.5\times10^{16}\times(\alpha_{833.4} + \alpha_{837})$ cm^{-3}, [V3O] = $8.5\times10^{16}\times(\alpha_{842.4} + \alpha_{848.7})$ cm^{-3}.

One of the most important oxygen related defects in silicon is the oxygen dimer. It contributes substantially to enhanced oxygen diffusion and clustering at elevated temperatures. In addition, the oxygen dimer is expected to play a key role in the formation of the center responsible for the light-induced degradation of silicon-based solar cells [11]. We have used different approaches including statistical ones [5, 11] and considered critically various assumptions to deduce the calibration coefficient for a determination of the oxygen dimer concentration from intensity of the RT measured absorption band at 10^{13} cm^{-1}, which is related to an local vibrational mode due to $O2_i$ [3, 5]. It has been concluded that the dimer concentration can be estimated as [O2i] = $7.2\times10^{16}\times\alpha_{1013}$ cm^{-3}. However, more additional studies are required to approve the value given above.

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