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MATERIALS SCIENCE IN SEMICONDUCTOR PROCESSING

Contact- less electrical defect characterisation of silicon by MD-PICTS

K. Dornich*, K. Niemietz, Mt. Wagner, J.R. Niklas

TU Bergakademie Freiberg, Institut für Experimentelle Physik, Leipzigerstr. 23, D-09596 Freiberg, Germany

Abstract

The visualisation of so far not detectable defects in electronic grade silicon was achieved by improving the sensitivity of a microwave detection system by several orders of magnitude. This approach to a new detection scheme opens possibilities for a variety of contact-less non-destructive electrical defect characterisation methods which can be applied to high-quality silicon wafers and even to thin epitaxial layers [Dornich K, Grundrig-Wendrock B, Hahn T, Niklas JR. Adv Eng Mater 2004; 598]. Electrical properties such as lifetime, mobility and diffusion length can be measured even at low injection levels with a spatial resolution only limited by the diffusion length of the charge carriers. The doping level of the material plays no major role. Due to the high sensitivity a microwave absorption signal caused by carrier emission from defects can be observed even in high-quality material at low injection levels. This allows for the first time the electrical investigation of the well-known thermal donor (TD) also in electronic grade p-doped silicon, which is not feasible with deep level transient spectroscopy (DLTS). Temperature treatment of such samples allows new insight into the transformation of TDs during annealing. Furthermore, the correlation with photoluminescence (PL) spectroscopy allows for an assignment of deep levels, which can be investigated by microwave-detected–photo-induced current transient spectroscopy (MD–PICTS) [Dornich K, Hahn T, Niklas JR. Freiberg Forschungsh B 2004; 327: 270; Dornich K, Hahn T, Niklas JR In: Proceedings of the MRS spring meeting vol. 864, 2005].

Keywords: MDP; MD-PICTS; Silicon; Defect levels; Thermal donor; Lifetime; Epi

1. Introduction

Well-established electrical characterisation methods for semiconductors have several drawbacks. However, some of them can be overcome by the development of new contact- less spatially resolving methods with high sensitivity like microwave-detected photoconductivity (MDP) and microwave-detected–photo-induced current transient spectroscopy (MD–PICTS) which are essential for analysing high-quality materials. This allows for photoconductivity measurements at very low injection levels with so far not achieved sensitivity and allows for a special evaluation of photoconductivity transients. Making use of a resonant microwave detection system, the methods can be applied to a variety of semiconductor materials. This enables the electrical characterisation of so far not detectable defects. Besides the possibility to furnish pieces of information such as lifetime (τ), diffusion length (L) and mobility (μ) mappings by the so-called MDP,

*Corresponding author. Tel.: +49 3731 392773; fax: +49 3731 394314.
E-mail address: KayDornich@gmx.de (K. Dornich).

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Nomenclature

E_A	activation energy (eV)
λ	wavelength (nm)
σ	resistivity (Ω cm)
τ	minority carrier lifetime (μs)
μ	mobility (cm^2/Vs)
L	diffusion length (cm)
T	temperature (K and °C)
Ω	capture cross section (cm^2)

the techniques offer a new kind of defect spectroscopy. Owing to the high sensitivity, at sufficiently low injection levels, thermal excitation of charge carriers out of defect levels filled during a photo pulse can be observed, see Fig. 1. After the light is turned off the photoconductivity transient signal consists mainly of two parts. The first part, a fast decay, corresponds to the minority carrier lifetime. This is followed by a much slower decay process due to the thermal emission of carriers out of defect levels. Important is the choice of sufficiently long

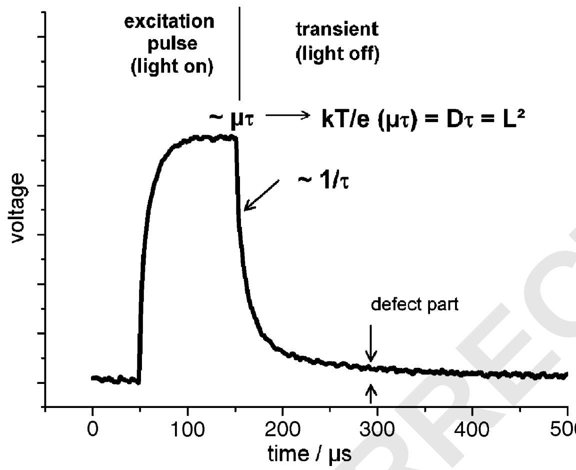

Fig. 1. Typical photoconductivity signal for a rectangular light pulse, p-silicon wafer.

photo-pulses in order to fill defect levels. Typical photo-pulse lengths are around 0.1–1 ms. The time constant of the slow emission depends on the defect activation energy, the defect capture cross section for electrons or holes, and on the temperature. Temperature-dependent measurements of such signals lead to defect specific photo-conductivity transients which can be used in a similar way as DLTS capacitance transients to gain specific information about the defects under investigation. This opens the possibility to obtain defect spectra as with DLTS measurements; however, contact-less, non-destructive, and highly spatially resolved [1]. Moreover, doping is not a critical parameter and the investigations are not restricted to just deep levels. We termed this kind of experiment MD–PICTS [2,3]. In contrast to DLTS, with MD-PICTS defects are filled by carriers via the valence or conduction band, or both. Therefore, MD-PICTS spectra on the one hand give access to a variety of defects so far not detectable by other electrical characterisation methods. On the other hand, some defects seen by DLTS are invisible by MD–PICTS. Depending on the concentration of the defects, the sensitivity of the detection system must be extremely high in order to see the defect specific slow part of the transient signal at all. At the same time, the light intensity must be even kept extremely low sometimes in order to prevent the photoconductivity

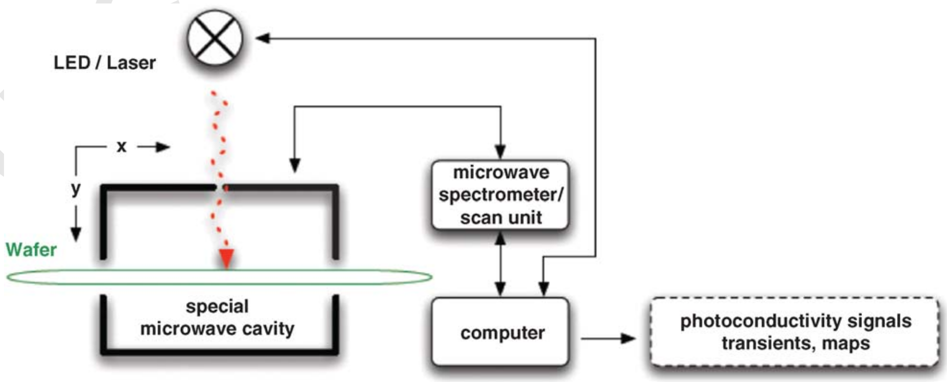

Fig. 2. Scheme of the experimental setup.

transient from being completely dominated by just the otherwise big part due to the free carrier lifetime. Just one example is taken from high quality 6'' electronic grade p-doped silicon wafers with specific resistivities around 12 Ωcm.

The experimental setup is depicted in Fig. 2. Absorption, not reflection, of the microwave field is used to measure the conductivity of the sample. The wafer is part of a special microwave system. Key feature is the appropriate coupling of the sample to a resonant microwave cavity. Due to the variety of electrical parameters accessible and high sensitivity there are now drawbacks in comparison with microwave reflection methods. For mappings the transients are recorded while the wafer is moving. In general, the wafer can be of unlimited size. For temperature-dependent measurements, such as MD-PICTS, the wafer must be part of a cryogenic system, which provides a further experimental challenge. The injection levels used correspond to an optical power of the light source in the range of about 10 μW to 10 mW depending on the defect concentration and type of semiconductor.

2. Results and discussion

Following the defect evolution during thermal treatment of p-doped silicon by MD-PICTS allows for the observation of two defect levels. Fig. 3a shows MD-PICTS spectra and Fig. 3b corresponding PL spectra of two temperature treatment steps. As grown samples and samples treated for 40 min at 450 °C show a defect at low temperatures in the MD-PICTS spectra, which we called PTD. This peak is believed to be due to the well known thermal donors (TDs) in silicon, which cannot be observed by DLTS in p-material because of the position of the Fermi level. The emission maxima are in this case at 133 K in as-grown and at 140 K in the 450 °C treated sample. After a 650 °C temperature step, the emission maximum shifts more than 40° to lower temperatures and is now located at 96 K. The activation energy shifts only slightly from $E_A = 0.13$ eV in the as- grown sample to $E_A = 0.11$ eV in the 650 °C treated sample. The temperature shift is due to a change in capture cross section, from $\sigma = 2 \times 10^{-18}\,\text{cm}^2$ in as-grown material to $\sigma = 2 \times 10^{-15}\,\text{cm}^2$ in 650 °C treated samples. The destruction of TDs at temperatures above 600 °C is well known in literature [4]. However, the MD-PICTS results suggest the transformation of such donors to electrically inactive trap states.

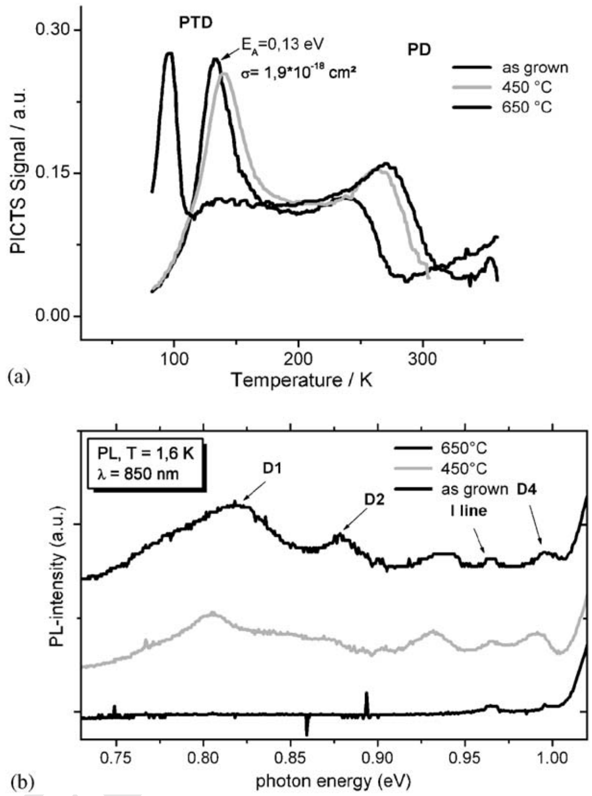

Fig. 3. a. MD-PICTS spectra of temperature treated electronic grade p-silicon: IR-LED $\lambda = 950$ nm, optical output 130 μW. b. PL spectra of temperature treated electronic grade p-silicon: $\lambda = 850$ nm, $T = 1.6$ K.

A second defect level with $E_A = 0.26$ eV in as-grown samples can be observed at 242 K. During temperature treatment, a rise in concentration and a shift of activation energy to around $E_A = 0.35$ eV can be seen. There is no information on the nature of this defect level called PD. This information may be obtained by further temperature treatment and correlation with PL spectra.

Three additional temperature steps at 750 °C, 900 °C and rapid thermal annealing (RTA) at 740 °C have been studied (Fig. 4a). There is a constant temperature shift of the PTD peak down to 78 K for the 900 °C temperature step accompanied by a drastic drop in concentration. This is believed to be due to the nearly complete destruction of the TD trap states at higher temperatures. The RTA step shows in MD-PICTS spectra only a drop in intensity in comparison to the 750 °C and 650 °C temperature steps. The PD defect shows a rise in concentration for the highest temperatures.

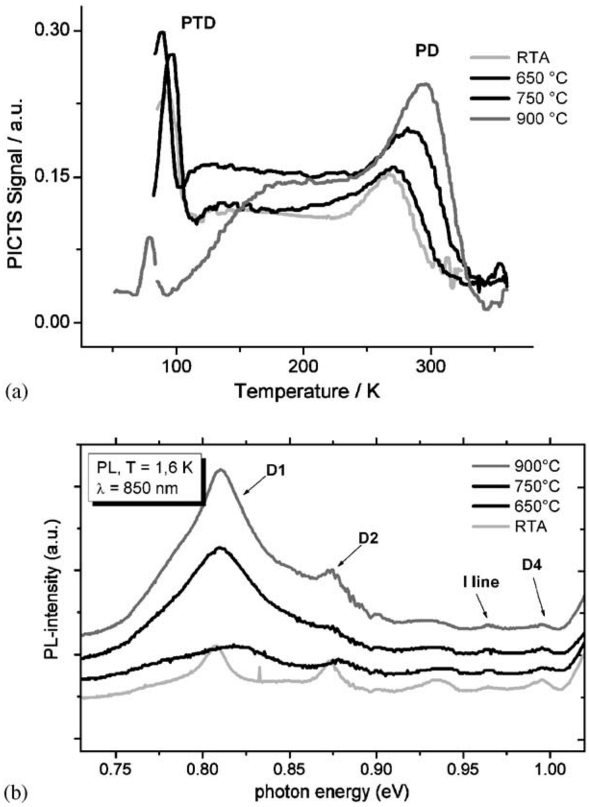

Fig. 4. a. MD-PICTS spectra of temperature treated electronic grade p-silicon at higher temperatures: IR-LED $\lambda = 950\,\text{nm}$, optical output $130\,\mu\text{W}$. b. PL spectra of temperature treated electronic grade p-silicon, $\lambda = 850\,\text{nm}$, $T = 1.6\,\text{K}$.

PL spectra for the same samples show besides several well known defect levels an increase in concentration for the D1 and D2 peaks at around 0.81 and 0.87 eV (Fig. 4b). Both defects are due to dislocations and kinks, jogs and stacking faults in

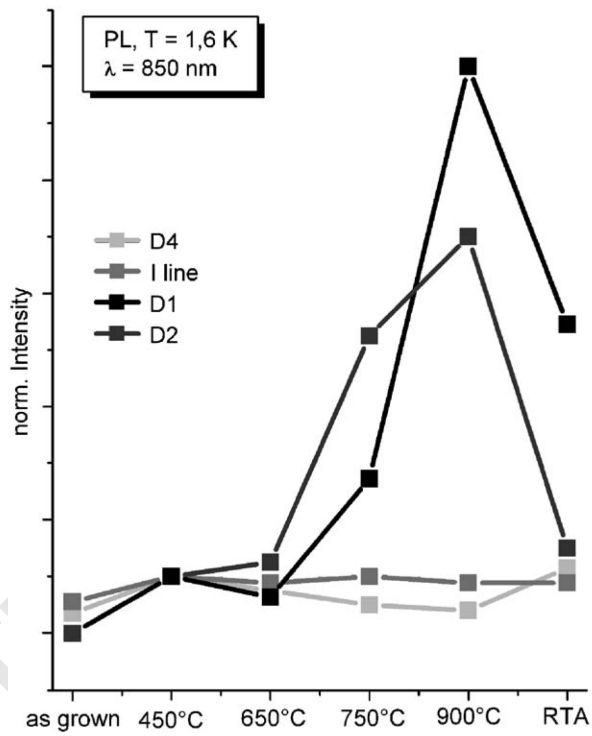

Fig. 5. PL peak intensity as a function of temperature treatment.

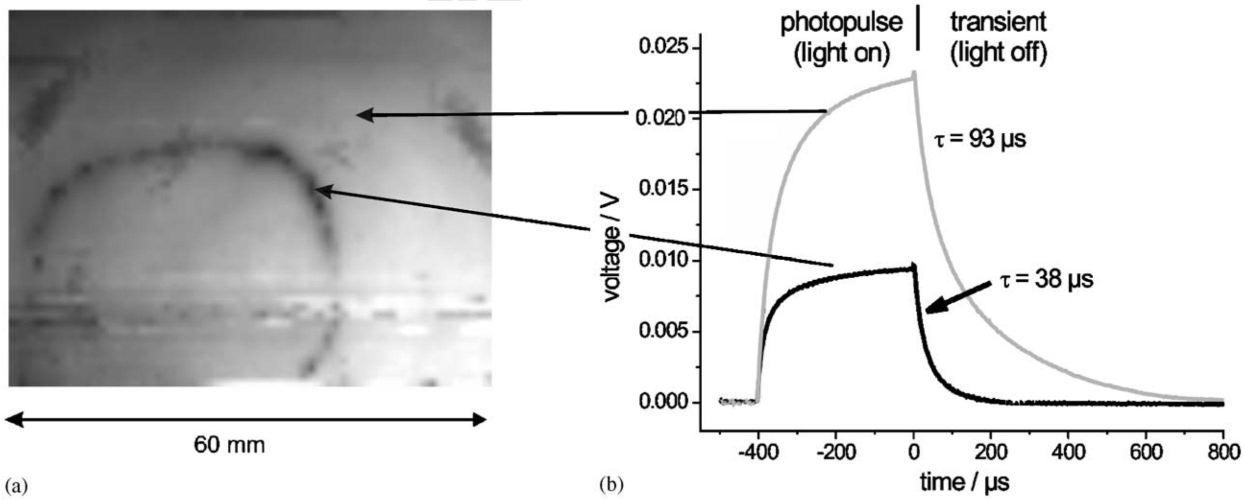

Fig. 6. Diffusion length map (relative differences not absolute values) of an passivated EPI layer n/n+, EPI: $15\,\Omega\text{cm}$, $50\,\mu\text{m}$, Substrate: $0.02\,\Omega\text{cm}$, size: $60 \times 45\,\text{mm}$ (a), corresponding photoconductivity transients at two different locations, the smaller transient corresponding to the circular structure (b), laser $\lambda = 657\,\text{nm}$, optical output 3 mW.

the vicinity of dislocations. The peak intensity in dependence of temperature treatment is shown in Fig. 5. Among others, the D4- and the I-line exhibit no intensity change with temperature treatment. However, the D1 and D2 lines increase their peak intensities with higher annealing temperatures. It is therefore suggested that the PD defect level in the MD-PICTS spectra is identical with the D1 and D2 peaks in the PL spectra.

Besides mapping of a variety of electronic grade and solar grade silicon wafers contact- less and fast electrical characterisation of epitaxial layers was the greatest challenge for the new method. Measurements are easily feasible down to an epi- layer thickness of about 2 μm, even on very high conductivity substrates. Doping levels are not critical down to below 0.1 Ωcm. Just one example of the mapping capability by MDP for an epi- layer is shown in Fig. 6a. A diffusion length map shows clearly the inhomogeneities within the layer. An absolute value of the diffusion length cannot be extracted without calibration. However the integral over the area underneath the photopulse is proportional to the square of the lifetime and such differences can be mapped. Under certain circumstances further information can be extracted by the variation of the excitation wavelength. Lifetime values differ by about a factor of 2.5, typical transients are shown in Fig. 6b. The investigation of the same layer at a higher wavelength of the exciting laser furnishes also information on interface defects on the backside of the epi- layer [3].

3. Conclusion

MDP and MD-PICTS are new contact- less, non-destructive methods for the characterisation of a variety of semiconductors [5]. The identification of two peaks measured with MD-PICTS in electronic grade p-silicon was accomplished. One of them is due to the family of TD defects. Temperature treatment of such samples results in a significant change in the position of the TD peak. This is believed to be due to the transformation of an electrically active TD state to an electrically inactive trap state at temperatures above 600 °C. At higher temperatures, the concentration of this defect peak drops rapidly suggesting the destruction of this defect level at temperatures above 900 °C. A second peak could be correlated with PL measurements and is assigned to defect levels in the vicinity of dislocations. MDP is as well suited for the electrical characterisation of a variety of epitaxial layers.

Acknowledgement

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