Materials Research Bulletin 58 (2014) 157–163

Contents lists available at ScienceDirect

Materials Research Bulletin

journal homepage: www.elsevier.com/locate/matresbu

Diffusion length and resistivity distribution characteristics of silicon wafer by photoluminescence

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ARTICLE INFO

Article history:
Available online 12 March 2014

Keywords:
A. Semiconductors
B. Luminescence
B. Optical properties
D. Diffusion
D. Electrical properties

ABSTRACT

Photoluminescence is a convenient, contactless method to characterize semiconductors. Its use for room-temperature silicon characterization has only recently been implemented. We have developed the PL efficiency theory as a function of substrate doping densities, bulk trap density, photon flux density, and reflectance and compared it with experimental data initially for bulk Si wafers. New developed PL intensity ratio method is able to predict the silicon wafer properties, such as doping densities, minority carrier diffusion length and bulk trap density.

1. Introduction

Photoluminescence (PL) was one of the useful characterization techniques for direct band gap and high quantum efficiency material in the past [1–4]. PL is particularly suited for the detection of shallow-level impurities, but can be applied to certain deep-level impurities, provided their recombination is radiative. Silicon, being an indirect band gap semiconductor, has low internal efficiency because most recombination takes place through Shockley–Read–Hall (SRH) or Auger recombination, neither of which emits light [5–8]. In spite of the low internal efficiency, PL is now used to characterize silicon wafer or epitaxial layer at room temperature [10]. In this paper, we use silicon photoenhanced recombination (SiPHER) PL system, allowing contactless and nondestructive room-temperature wafer characterization with 532 nm or 827 nm wavelength for excitation source [9]. The high intensity laser source, of 1 μm or 1 mm diameter, is able to map entire wafer at modest resolution or scan a smaller area at higher resolution [6]. This PL system detects two signals, PL intensity and surface reflectance (SR) intensity, from the test sample. The PL intensity is strongly dependent on surface recombination velocity, bulk lifetime, and trap density [10,11]. The SR intensity depends on surface condition, layer thickness and optical properties. More recently, it has been used to characterize Si solar cell material, copper indium gallium selenium (CIGS) compound material band-gap characterization, and map iron densities in Si [12,13].

To test our PL measurement, we first compared PL and surface photovoltage (SPV) [14] measurements. PL intensity mapping profile is shown in Fig. 1(a) and the minority carrier diffusion length L_n mapping profile is shown in Fig. 1(b) for one particular p-type Si bulk wafer by PL system and SPV measurement, respectively. All of the measurements in this paper are made at room temperature. In order to differentiating wafer map characteristics, we damaged the wafer on purpose by touching a finger in region A and by scratching with a metal pointer in region B and subsequently annealed at 1100 °C for 2 min. Both figures clearly show the degradation in regions A and B. The metal scratches lead to significant PL and L_n reduction as expected. The finger-touched region A exhibits more SPV than PL degradation and shows a region beyond the original finger touch area that affects the PL intensity. The higher resolution of the PL map is evident from these maps. From an analysis of the data, we conclude that the finger touch contamination increases the surface and bulk recombination rate whereas in the metal-scratched region it is mainly the bulk recombination rate that is increased. These measurements established the usefulness of PL measurements for us [10].

Next we correlated L_n with PL intensity for no damaged p-type bulk wafer with well surface passivation in order to removing surface recombination effect for both measurements. The PL intensity data of such wafers are more difficult to correlate to minority carrier diffusion length since PL intensity is relative unit. We developed new method, PL intensity ratio, to convert from the PL intensity to electrical parameters such as trap density, surface

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http://dx.doi.org/10.1016/j.materresbull.2014.03.002
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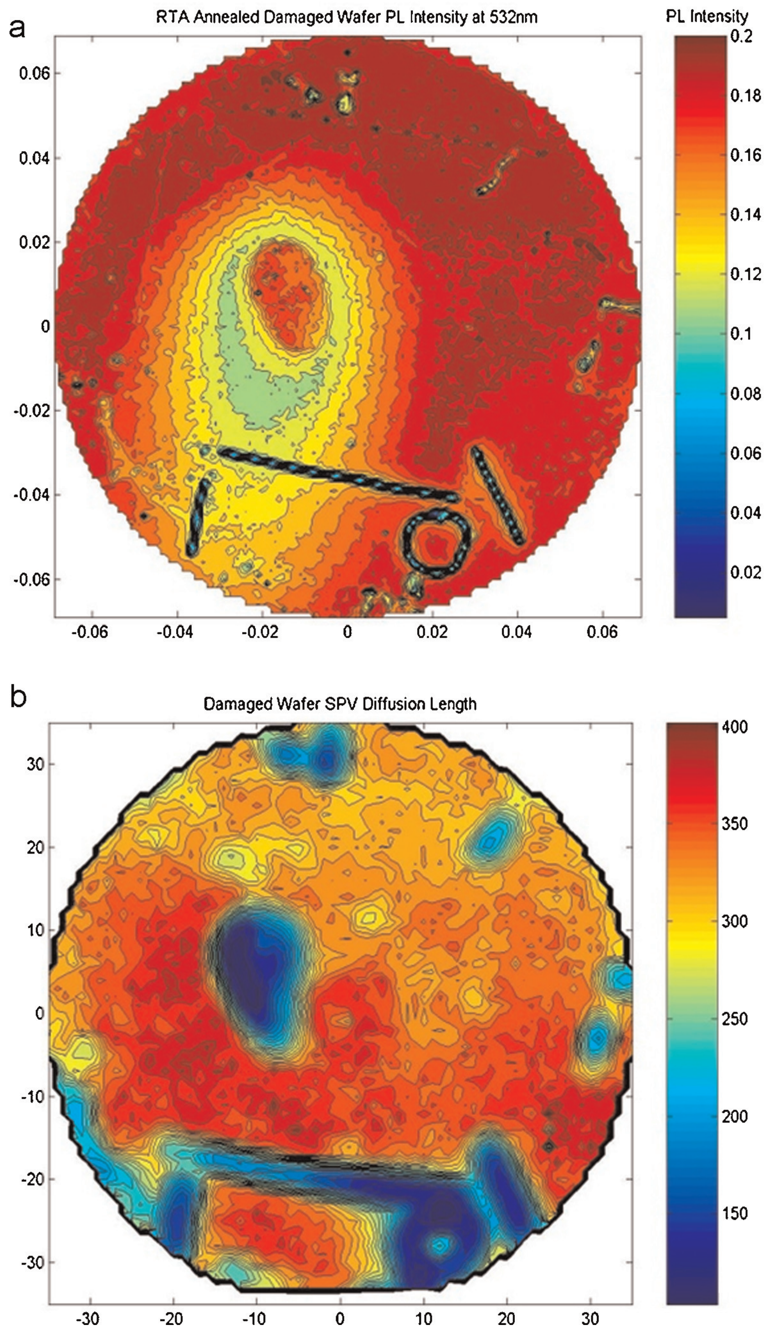

Fig. 1. (a) Photoluminescence and (b) SPV maps of a bulk Si wafer. Region A: touched with a finger, B: scratched with a metal pointer [10].

recombination velocity, and minority carrier lifetime or diffusion length. In this paper, we focus on correlation between PL intensity and minority carrier diffusion length.

2. Theory

We have developed one-, two- and three-dimensional models of the carrier distribution in semiconductors following light excitation and use these distributions to calculate PL signals to extract the various doping density and recombination components. Here we confine ourselves to the one-dimensional case. To develop the new PL model, we start with the steady-state continuity equation for the excess minority carrier generation and the PL efficiency described by the one-dimensional excess carrier generation equation and given by [15]

$$\eta_{PL} = \frac{BL_n}{\Phi}\left[\begin{array}{l} P_0\left(C_1\left(1+e^{-\frac{d}{L_n}}\right)+C_2\left(1+e^{\frac{d}{L_n}}\right)+\frac{C_3}{\alpha L_n}(1+e^{-\alpha d})\right) \\ +C_4 e^{-\frac{2d}{L_n}}+C_5 e^{\frac{2d}{L_n}}+\frac{C_6}{1+L_n\alpha}e^{-\left(\frac{1}{L_n}+\alpha\right)d}+\frac{C_7}{1-L_n\alpha}e^{\left(\frac{1}{L_n}+\alpha\right)d} \\ +\frac{C_8}{1+L_n\alpha}+\frac{C_9}{1-L_n\alpha}+C_{10}+\frac{1}{\alpha L_n}(C_{11}e^{-2\alpha d}+C_{12})+\frac{C_{13}d}{L_n} \end{array}\right] \quad (1)$$

where C_1–C_{13} depend on the minority carrier diffusion constant D_n, the minority carrier diffusion length L_n, and the surface recombination velocity s_r. The PL efficiency η_{PL} depends on the photon flux density Φ, the radiative recombination coefficient B, the majority carrier density p_0, the absorption coefficient α, the reflectivity R, the minority carrier diffusion length L_n, the sample thickness d, and the surface recombination velocity s_r.