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ORIGINAL ARTICLE

The effective carrier lifetime measurement in silicon: The conductivity modulation method

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Abstract Dark, gamma-induced conductivities and conductivity modulation in silicon material will be investigated for the development of carrier lifetime measurement. The present work includes a simple method for finding the carrier lifetime variation from the measured conductivity under dark and gamma irradiation conditions. It will be concluded that an improved material evaluation in the area of semiconductors and nano-materials are expected to improve the efficiency of solar cells and other opto-electronic devices.

1. Introduction

The lifetime measurement is normally used in one way or another to assess material quality. High lifetimes are indicative of good material, while low lifetimes might point to problems such as inadequate crystal growth techniques that introduce dislocations or high concentrations of impurities in the semiconductor material. Processing of various semiconductor devices can also be effectively monitored and improved by systematic lifetime measurements. Previously the study of semiconductor materials, devices and circuits, lifetime measurements were useful in gaining a better understanding of generation and recombination mechanisms. With improved fabrication technology, the focus shifted away from theoretical studies to processing-related lifetime testing. However, with the new devices such as large area power devices, metal-oxide–semiconductor MOS devices and high-efficiency solar cells, there has been a considerable interest in lifetime measurements that gives an explanation to the physical recombination processes within the device. However, the measurement of carrier lifetime in silicon wafers was studied in the past three decades. This parameter is still required to be determined accurately for new composites and nano-materials. On the other hand, the conductivity modulation could alter the distribution of charge carriers available for conduction. Thus, the excess conduction loss can occur as conductivity modulation proceeds and the forward voltage will be lowered to the steady-state value, (Moslehi, 1991; Stephens, 1996; Carsten, 2001; Zhang et al., 2001; Brown et al., 2001; Nagel et al., 1991).

The present work discusses the evaluation of carrier lifetimes based on a method developed earlier by Elani et al. (2005) and more recently by Elani (2008). It will be concluded that the conductivity modulation (conductivity changes) measurement can lead to the determination of carrier lifetime. This

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parameter is very important for silicon fabrication in many electronic devices such as solar cells, sensors, nuclear detectors, switches and other bipolar or opto-devices. The other benefit of the current research work lies within the improvement of the computerized in-line carrier lifetime systems, such as the microwave relaxometer and wafer lifetime tester (Telecom-STV, 2003).

2. Method of analysis

Two main methods for determining the carrier lifetime are known. The first one is intended to measure the "transient" effective lifetime by injecting the silicon material with excess charge carriers from typical external sources such as electric field, optical pulses, gamma radiation and others (Eikelboom and Burgers, 1994; Cuevas and Sinton, 1997; DiGulio et al., 1981; Stewart et al., 2001; Maekawa et al., 1995). Such sources will generate excess carriers and then the effective lifetime could be determined easily. The second method is known as the steady-state technique which requires only a fixed value of carrier generation (Sinton, 2004). If surface effects are neglected and a uniform photogeneration is assumed, the bulk carrier lifetime:

$$\tau_b = \frac{\Delta n}{U} \tag{1}$$

where Δn is the excess charge carriers (cm^{-3}) and U is the net recombination rate in the bulk (cm^{-3} s^{-1}). Now, assuming σ_D as the dark conductivity which is given by:

$$\sigma_D = \frac{I}{2\pi \cdot d \cdot V} \tag{2}$$

where I is the injected current (A), V is voltage developed across the sample/wafer; and d is the inner spacing between probes (cm). If σ_γ is the conductivity due to gamma radiation, then the difference in conductivity is defined (the conductivity modulation $\Delta\sigma$) as:

$$\Delta\sigma = \sigma_\gamma - \sigma_D \tag{3}$$

Based on the previous technique reported by Elani et al. (2005), the effective lifetime of minority carrier is then reduced to:

$$\tau_{\text{eff}} = \frac{\Delta\sigma}{J \cdot (\mu_n + \mu_p)} \cdot W \tag{4}$$

The previous approach was fully adopted from a recent published paper by Elani (2008). The lifetime determination is considered in this work only under dark and gamma conditions. The lifetime level could be distinguished from its magnitude (ps, ns, µs, ms) according to sample size and device or wafer application (Taylor, 2005; Zaroff and Brophy, 1963; Ravi, 1981; Shimura and Huff, 1985; Kishimoto, 1996; Kishimoto et al., 1998; Bentzen et al., 2005; Sinton Consulting Inc., 2006).

3. Experimental procedures and results

3.1. Samples

A number of n-type monocrystalline silicon materials is used throughout the present work. Ten wafers are taken from the same batch. These wafers were supplied from Arkansas University, USA. The silicon samples are numbered horizontally and vertically across the surface of each wafer. For example, the symbol L3S4 means sample no. 4 line 3 (i.e. line zero starts from the diameter and up for each wafer and so on). A special mask was used with opening windows with an approximate area of 4 mm × 2 mm.

3.2. Experimental technique

A Jandel in-line four-probes assembly "ILFP" is used normally for measuring the resistivity across each wafer (Jandel Ltd., UK, 2001). The sample geometry was controlled by the probes spacing. A current is passed through the outer two probes; and the potential developed across the inner two probes is measured. The ILFP technique is used here to measure the dark conductivity σ_D under dark conditions (no light or external excitation) based on Eq. (2). The induced change of gamma conductivity σ_γ in silicon samples could be realized when samples are exposed to gamma rays. The radiation source was a gamma cell 220 Model no. 246 with a Cobalt-60 source containing 24,910 Curies. Low intensity gamma radiation is considered with exposure times of 1–2 h which is equivalent to nearly 6323 and 12,647 Gy irradiation doses, respectively. The conductivity modulation values are then defined as the difference between gamma conductivity and dark conductivity according to Eq. (3) and the effective lifetime was determined from Eq. (4).

3.3. Dark, gamma conductivity and conductivity modulation

As mentioned by Elani et al. (2005), it was found that the dark conductivity σ_D increases at higher injected current levels and the average change in σ_D lies between 60 and 200 Ω^{-1} cm^{-1} across the levels in most silicon wafers.

The uniformity of bulk resistivity is an important factor for establishing the conductivity modulation mode. For instance, by exposing the silicon wafers to gamma radiation at different doses and time levels, an increase in their conductivity are obtained, and this may be attributed to the excess charge carriers produced by gamma irradiation and this will lead to an improvement in the conductivities of nearly 2–3 times of their initial values. This result could be also explained from the fact that the conductivity modulation causes a sharp increase in the gamma-induced conductivity σ_γ. In fact the conductivity

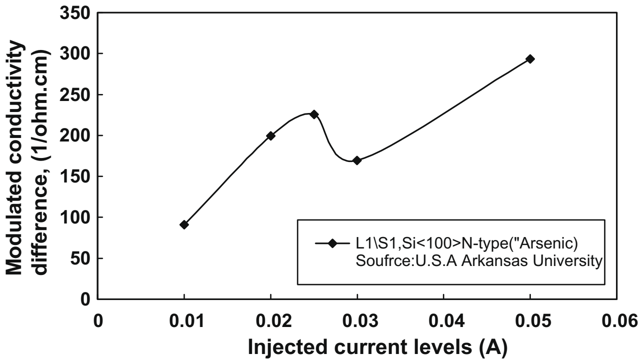

Figure 1 The variation of modulated conductivity differences with injected currents at the central region in Si#1 wafer.