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Recombination Lifetimes Using the RCPCD Technique: Comparison with Other Methods

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Recombination Lifetimes Using the RCPCD Technique: Comparison with Other Methods

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ABSTRACT

The theory and operation of the resonance-coupled photoconductive decay (RCPCD) technique is described. Examples are presented of data measured on a wide variety of sample types.

1. Objectives

The RCPCD technique has been applied to a variety of wafer and thin-film materials. Using this technique, we can measure recombination lifetime over at least three decades of injection level. We can also measure relative values of minority-carrier mobility and diffusion length. By scanning the excitation wavelength, we can measure spectral response and photoconductive excitation spectra. Deep-level impurities have been detected by several variations of RCPCD.

2. Technical Approach

The electronics industry has adopted a technique called microwave reflection as a standard technique for silicon wafer characterization. Using a microwave generator that operates in the 10–30-GHz frequency range acts as a probe beam, which is reflected by the free carriers of the semiconductor. A pulsed light source, which is usually a GaAs laser, is used to excite excess carriers. The variation of the reflection coefficients of microwaves from the free carriers was calculated by Kunst and Beck and is a very nonlinear function of carrier concentration. At a sample conductivity larger than about 1000 ohm-cm^{-1}, the reflection coefficient saturates at unity for X-band frequencies and measurement becomes impossible. Also, one must use an excess-carrier injection level that is generally less than 0.05 times the background carrier density in order to get a linear response. Therefore, the technique is limited to measuring the low-injection lifetime.

3. Results and Accomplishments

Because of these limitations of the microwave reflection technique, we developed a new technique for PV-quality silicon and other PV materials. This technique has fewer limitations as compared to microwave reflection. Our system is again a pump-probe technique, using an optical pump and a high frequency (400–900 MHz) probe, which penetrates most wafers with common doping levels. By varying the excitation wavelength, one can make lifetime-depth probes of standard (300–400 μm) wafers. Also, we have measured a linear response over more than three orders of magnitude of injected carrier concentration. Measuring lifetime versus injection level is called injection-level spectroscopy (ILS).

The RCPCD technique was developed at the National Renewable Energy Laboratory (NREL) and has been used on more than 8000 samples, ranging from small-area thin films to 350-μm-thick, 250-mm-diameter silicon wafers. There are no particular shape requirements, and samples of irregular shape are routinely measured.

The RCPCD technique has been especially successful in measuring some small-band semiconductors such as InAs and mismatched InGaAs grown on InP substrates. The latter are not easily measured by time-resolved photoluminescence due to the lack of sensitive photodetectors in the infrared (IR) wavelength region. The sample is coupled to the electromagnetic field of a small antenna. A number of antenna geometries have been tested including a several-turn loop, a patch antenna, and other proprietary configurations. The antenna is connected to a detection system through a comparator circuit, which compares the antenna circuit impedance with a standard value. The sample lies on an insulating, moveable platform in an enclosure that shields the latter from the external world. The enclosure also acts as a directional reflector for directing rf fields toward the sample. The antenna-sample system behaves like an antenna array with active and passive elements. The complex impedance of the antenna can be described as a combination of radiation resistance and reactance. The antenna, circuit elements and enclosure are configured in such a way as to produce a high Q and sharp resonance. When the semiconducting sample is placed in the proximity of the antenna, the mutual impedance modifies the input impedance of the antenna circuit. We write this coupled impedance, Z_{in}, looking into the antenna terminals, as:

$$z_{in} = Z_{ant} - \frac{Z_{12}^2}{Z_s}.$$

Here, Z_{ant} is the impedance of the isolated antenna, Z_s is the impedance of the sample, and Z_{12} is the mutual impedance. The mutual impedance depends primarily on the antenna-sample spacing, but it also depends on the sample size and conductivity. In operation, the antenna-sample spacing is varied until the antenna-system impedance matches that of the comparator circuit; i.e., a null is achieved in the detection circuit. Figure 1 shows the impedance-frequency curve of a silicon wafer coupled to the antenna system. The sample spacing is a parameter and the data show that the position changes both the peak and amplitude of the resonance. With the spacing, d, equal to zero, the Q is significantly lowered and the impedance cannot be nulled relative to a 50-ohm reference.

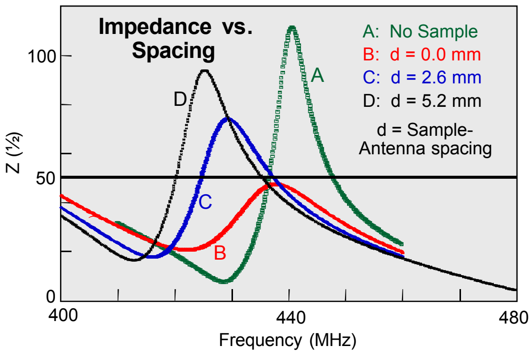

Fig. 1. Antenna impedance of a silicon wafer versus sample-antenna spacing.

During pulsed excitation, we can write the antenna-circuit impedance as:

$$z_{in} = Z_{ant} - Z_{12}^{2} [\ {}_{s} + \quad {}_{s}(t)]$$

Figure 2 shows how the resonance curve shifts with conductivity, by measuring the impedance-frequency curve with samples of the same physical size but different doping levels. This shift is the basis of the RCPCD technique.

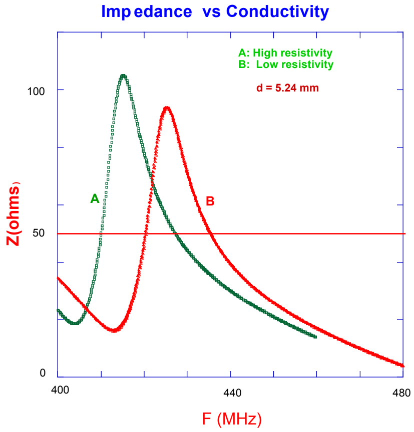

Fig. 2. Antenna impedance of two wafers of different conductivity.

Figure 3 is a simplified schematic of the measurement apparatus. The unbalanced signal (produced by photoconductivity) is amplified and rectified to produce a dc transient representing the photoconductive decay. The minimum time response of the system based on a coil antenna is about 20 ns. Faster response has been observed with some other configurations, but these antenna systems are still in the testing phase. Figure 4 shows data that were obtained using both RCPCD and microwave reflection using the same crystals and light source. These crystals were commercial, CZ-grown wafers that had resistivities in the range of 100 ohm-cm^{-1}. In this figure, the upper curves are RCPCD data and the lower curves are -wave reflection data. One can see from the figure that the RCPCD signal amplitudes are 100 to 1000 times larger for comparable signal-to-noise figures.

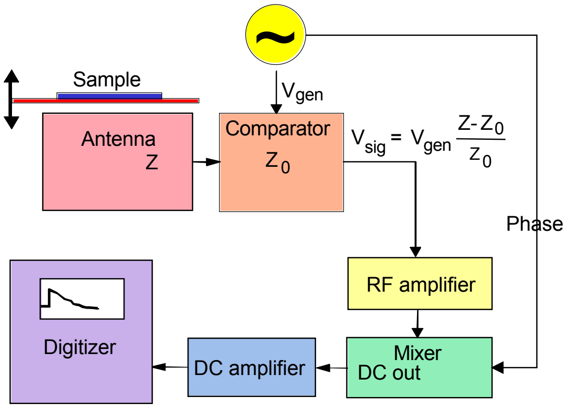

Fig. 3. Simplifed circuit schematic

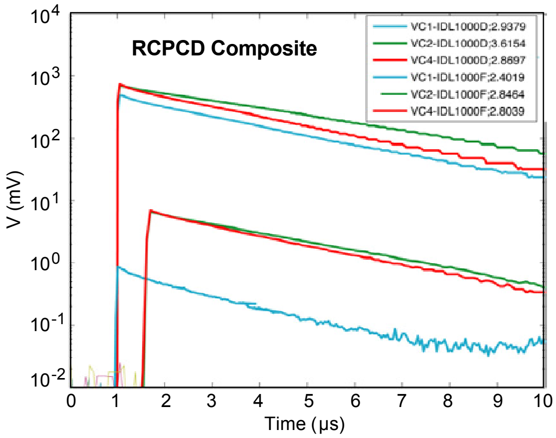

Fig. 4. Data using RCPCD (upper) and m-wave reflection (lower) for a set of three wafers. The excitation source was identical for both data sets.

4. Conclusions

RCPCD is a very promising new technique for a range of applications and has some advantages over microwave reflection.

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15. **SUBJECT TERMS**

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