Optical Detection of Radiation-Induced Leakage Current in Ultra-Thin Oxides

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Abstract-- Leakage currents in a variable-thickness ultra-thin oxide structure (1.0-6.5 nm) are observed to be substantially enhanced by X-ray radiation-induced damage as detected by second-harmonic generation (SHG). SHG provides a contactless, noninvasive alternative to electrical characterization.

I. Introduction

Recent research in non-linear optics facilitated by advances in ultra-fast laser technology has shown optical second-harmonic generation (SHG) to be a sensitive probe of buried interfaces [1]. SHG is a contactless and non-destructive technique that can be used to monitor charge-carrier dynamics in ultra-thin oxides [2]. We have found that SHG is a useful tool for \textit{in situ} measurements that are difficult if not impossible to carry out by conventional electrical probes. As microelectronic devices decrease in size, so also are oxide thicknesses drastically reduced. It has been observed that ultra-thin oxides may show a low-field leakage current that can cause performance and reliability problems in MOS devices. These leakage currents can be significantly enhanced by exposure to ionizing radiation [3,4]. The observed enhanced leakage currents can be attributed to an inelastic tunneling process mediated by radiation-induced neutral traps in the oxide [5].

In particular, optical SHG has become an extremely useful technique for surface and interface studies of Si/SiO\textsubscript{2} structures. Crystalline Si is a centrosymmetric material and thus will not give an SHG signal, but at the Si/SiO\textsubscript{2} interface the symmetry is broken and thus a time-independent SHG signal will result. In addition, the second-harmonic signal is very sensitive to changes in the magnitude of the electric field across the interface. In the experiments described here, optical SHG detects time-dependent electric fields at the interface arising initially from multi-photon induced injection of electrons (in this case, not holes) through the interface into the oxide. The electrons are subsequently trapped at the oxide surface, which results in a charge-separation induced electric field. As the initially trapped electrons are transported across the oxide and recombine with holes on the Si side of the interface, the measured field is reduced. Clearly, optical SHG can be a valuable tool to study dynamical electronic processes including injection of charge carriers, trapping in and on the surface of the oxide and transport [6]. Thus it is clear that optical second-harmonic generation is ideally suited to measure and characterize leakage currents in thin oxide films.
Electric field-induced second-harmonic generation (EFISH) is governed by the following equation:

\[ I^{(2\omega)}(t) = \left| \chi^{(2)} + \chi^{(3)} E(t) \right|^2 I^{(\omega)} \],

where \( I^{(\omega)} \) and \( I^{(2\omega)}(t) \) are the intensities of the fundamental and time-dependent SHG signals, \( \chi^{(3)} \) is the third-order non-linear susceptibility, \( \chi^{(2)} \) is the effective second order susceptibility from all other sources and \( E(t) \) is photo-induced electric field [7].

In this paper we report optical second-harmonic measurements to detect and characterize leakage current in radiation damaged and undamaged Si/SiO₂ structures. The most detailed measurements were carried out on a single Si/SiO₂ sample with an oxide layer, that varied in thickness monotonically from 1.0 nm to 6.5 nm. This allows us to investigate the thickness dependence of leakage current on an oxide layer with no variation in processing conditions. We observe that, in the unirradiated case, leakage current, which is measured by detecting the reduction in electric field due to tunneling-facilitated transport of electrons across the oxide, became significant only at the smaller thicknesses. However, when after radiation exposure, the sample showed large leakage currents at all thicknesses. Standard electrical measurements, such as capacitance-voltage (C-V) and current-voltage (I-V), are difficult to interpret when the oxide thickness varies in the active device area. We observed similar SHG results in other oxides of comparable thickness, emphasizing the reproducibility of the results. Clearly, the optical SHG technique, being contactless and non-invasive, can provide important information about carrier transport through ultrathin oxides.

II. Experimental Configuration and Results

In our experiment we used a sample with a Si(100) substrate and an initial SiO₂ oxide thickness of 6.5 nm. The sample was dipped into a 1% solution of hydrofluoric acid at a controlled speed to provide a gradually decreasing thickness of the oxide [8-10] film. A Ti:sapphire laser was used operating at 800 nm (1.5 eV) with 150 fs FWHM pulses, repetition rate of 76 MHz and average power of 250 mW. The measurements were taken on both non-irradiated and irradiated [20Mrad(SiO₂)] samples.

![Figure 1. A typical time-dependent SHG signal taken on an unirradiated sample at a thickness of about 1.0 nm.](image)

It is shown in figure 1 that at a low average-beam power the signal begins at a finite level, which implies that there exists a time-independent \( \chi^{(2)} \) contribution. The SHG signal is always taken at the same beam power independent of whether the average beam power is high or low. At a high beam power, we observed a monotonically rising SHG signal which approaches a saturation level. At this power level, the laser functions both to inject electrons into the oxide and to measure, by SHG, the resulting increasing field at the interface. After decreasing the average beam power we observed a marked decrease in the...
SHG signal. We attribute this to a decrease in the electric field, arising from increased transport and subsequent recombination of the surface trapped electrons with holes at the interface. This current leakage effect significantly increases after irradiation.

Figure 2. Exponential fits of time-dependent SHG signals from the thick part of the oxide layer (a – high average beam power; b – after the beam power is reduced to a lower average level)

Figure 2 shows the data from the thick part of the oxide layer of a sample (approximately 6.0 nm). Before irradiation, the SHG intensity remained at the same level after the beam power is decreased indicating little or no leakage current. After irradiation, the signal significantly decreased indicating an increase in electron transport. Hence, the radiation-induced defects [3]-[5] in the SiO₂ can significantly enhance the conduction current through these thin oxides [11]. However, after a significant length of time, the irradiation effects disappear, and the signal approaches the pre-irradiation behavior. Thus the particular defects causing this leakage current are clearly metastable.

Figure 3. Exponential fits of time-dependent SHG signals from the thin part of the oxide layer (a – high average beam power; b – after the beam power is reduced to a lower average level)

Figure 3 shows the results of measurements performed on a thin part of a sample (approximately 1.0 nm). Before irradiation, we observed an increase at high laser power, with a decrease at low laser power in the interface electric field, the latter due to tunneling effects in thin oxides. After irradiation, the saturation levels of the signals are much lower. The decrease in the photo-induced electric field due to the
decrease of the average beam power is much faster. We attribute this behavior to the fact that after irradiation the oxide is almost transparent to the trapped electrons, which tunnel back through the oxide and recombine. It has been shown in previous electrical tests that leakage currents can be significantly enhanced after irradiation, due to an inelastic tunneling process mediated by radiation induced neutral traps in the oxide [3,4,5]. The optical measurements we have performed here appear to be sensitive to these kinds of leakage effects at lower dose levels than observed in electrical studies, allowing use to probe their time dependence quite sensitively. The characteristic lifetime of these defects appears to be several dozen hours. We will discuss the nature of these defects and the resulting conduction in the full paper.

III. Conclusions

In this research, we have demonstrated that second-harmonic generation is a very useful technique for the characterization of current leakage in X-ray damaged ultra-thin oxides. We performed time-dependent measurements, using an intense ultra-fast pulsed laser, which provides dynamical information about injection, trapping, detrapping, transport and recombination processes in thin layers of SiO₂ on Si. In addition, we have shown for the first time that optical SHG measurements can be performed effectively on an oxide sample with gradually varying thickness (from 1.0 nm to 6.5 nm). The significant differences between the carrier-dynamics behavior in thin (1.0 nm) and thick (6.0 nm) oxide layers on the same sample using SHG give unique insight into leakage-current mechanisms in thin oxide films.

Acknowledgments

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References