Contactless Ultra-Fast Laser Probing of Radiation-Induced Leakage Current in Ultra-Thin Oxides

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***Abstract*—Radiation induced leakage current in a variable-thickness SiO_2-on-Si structure (1.0–6.5 nm) is detected and characterized by a novel technique, time-dependent electric field-induced second-harmonic generation (EFISH). The role of second-harmonic generation (SHG) for in situ monitoring of the DC field across the oxide and its utility in understanding the dynamics of the carriers in response to their photo-injection is discussed. Plausible mechanisms responsible for radiation-induced leakage current through thin oxides are used to explain the experimental results.**

***Index Terms*—Laser measurements, semiconductor device radiation effects, X-ray effects.**

I. INTRODUCTION

THE Si/SiO_2 interface is arguably the world's most economically and technologically important material interface. The continued scaling of integrated devices and the continued adherence to Moore's law has resulted in ever-thinner SiO_2 gate dielectrics. Leakage currents in thick oxides have been found to be significantly enhanced by exposure to ionizing radiation [1], [2]. As gate oxides become thinner than ~3 nm, direct quantum mechanical tunneling through the dielectric barrier is found by electrical measurements to be the dominant contribution to leakage current. This type of radiation-induced leakage current (RILC) is often attributed to an inelastic tunneling process, mediated by radiation-induced neutral traps in the oxide [3], [4].

Recent research in nonlinear optics facilitated by advances in ultra-fast laser technology has shown optical second-harmonic generation (SHG) to be a sensitive probe of semiconductor-to-insulator interfaces that in turn gives information on transport, trapping and recombination processes associated with the device structure [5]. These measurements are performed on samples without gate electrodes, so they are potentially suitable for monitoring film quality during wafer processing.

In this work, radiation-induced changes in the SHG signals obtained from oxide films of variable thickness are presented. These measurements provide information about defects that are responsible for leakage currents particularly in sub-3-nm oxides, which are difficult to extract from conventional electrical measurements. The conceptual background behind the dynamics of the SHG response, considering different transport mechanisms for carriers across oxides, is presented in Section II. The experimental technique of generating SHG signals from variable thickness oxides is discussed in Section III. A phenomenological model is used to interpret the results in Section IV.

II. CONCEPTUAL BACKGROUND

A. Second Harmonic Generation

SHG is a contactless and nondestructive technique that can be used to monitor charge-carrier dynamics in ultra-thin oxides [6]. In the experiments described here, optical SHG detects time-dependent electric fields specifically at the interface, with little or no contribution from the bulk Si or SiO_2. The electric field at the interface arises from charge separation due to single photon/multiphoton excitation of electrons in the valence band, and the subsequent transport of these electrons by diffusion, tunneling, or a combination of both across the oxide [7]. This approach is often referred to as electric field induced second harmonic generation (EFISH) [8].

The electric field-induced second-harmonic generation (EFISH) signal is governed by the following equation

$$I^{(2\omega)}(t) = \left|\chi^{(2)} + \chi^{(3)}E(t)\right|^2 \left(I^{(\omega)}\right)^2 \quad (1)$$

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 nonlinear susceptibility, $\chi^{(2)}$ is the effective second-order susceptibility from the interface and all other sources, and $E(t)$ is the photo-induced electric field [9].

The time-dependent electric field is a measure of the electron density accumulated at the free oxide surface. The electric field across the interface can increase transiently when a laser pulse hits the sample. This transient behavior has been previously observed and has been attributed to the separation of electrons and

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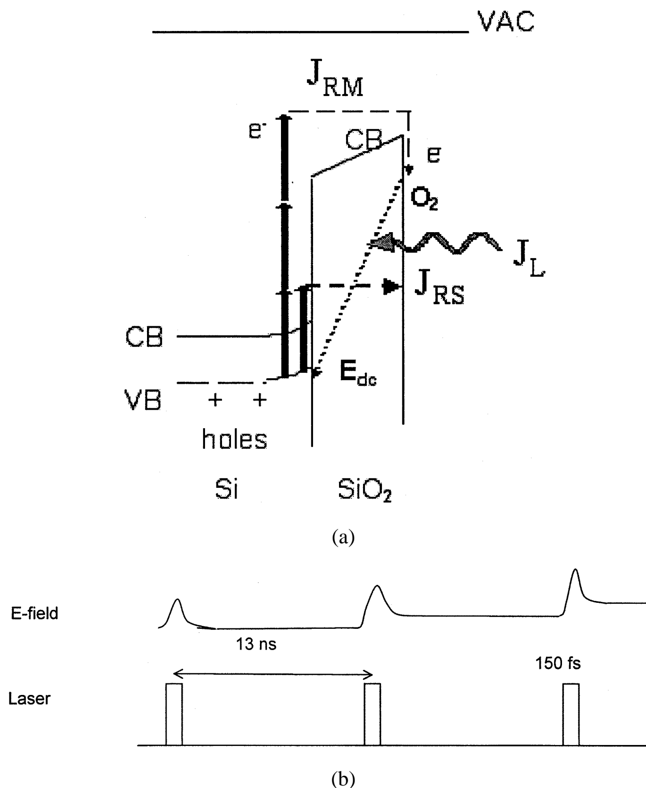

Fig. 1 Schematic diagram of the EFISH experiment. (a) Electron transfer process within Si/SO_2; (b) pulse to pulse increase in electric field across the interface.

holes at the Si/SiO_2 interface [13]. After each laser pulse hits the sample, a small number of electrons will be excited to an energy above the oxide barrier, which will allow transport through the oxide to the surface. These electrons may be trapped on the surface of these oxides [8]. This will result in a cumulative pulse-by-pulse increase in the field at the interface (see Fig. 1) until the system saturates as the traps are filled. Holes do not significantly contribute to this process because at the Si/SiO_2 interface, more energy is required to overcome the oxide barrier than is needed for electrons.

For thin oxides ($\sim<3$ nm), recombination arising from quantum mechanical tunneling of the surface-trapped electrons competes with the trapping process, which tends to lower the electric field at the interface as measured by SHG. Thus, in the absence of optical excitation, these initially surface-trapped electrons leak through the thin oxide layer and recombine with holes on the Si side of the Si/SiO_2 interface, and the induced electric field tends to decrease.

B. Leakage Mechanisms in Oxides

Previous experiments involving electrical measurement on 4–6-nm MOS samples showed that ionizing radiation can induce leakage current in oxides [1], [2]. In these studies, gate current versus gate voltage ($I_g - V_g$) characteristics were measured and evaluated after electrical stress (causing stress-induced leakage current, SILC) as well as after subjecting the sample to irradiation. It was shown that both radiation-induced leakage current and SILC have a similar conduction mechanism: trap-assisted electron tunneling across the oxide.

Irradiations performed at different gate biases showed the highest induced leakage current when an electric field near zero was applied during irradiation; the induced leakage decreased with increasing oxide fields. Ceschia *et al.* suggested that the traps/defects involved in the electron conduction are neutral; however, these defects likely have a positively charged precursor [2]. Candidates for precursor defects include hole traps (such as an E' center [14], which becomes neutralized after capturing a hole); however, the microscopic character of the traps/defects involved in the process is not yet resolved. It has been suggested that both RILC and SILC originate from the same defect [15].

A competing idea for the microscopic origin of SILC is that the defect responsible for the induced leakage is hydrogen-related. Blöchl and Stathis have suggested a two-step inelastic tunneling mechanism via a defect, in which voltage greater than the level shift between uncharged and charged states of the defect must be applied [17]. They investigated several different structures via density functional theory calculations and proposed that the trap mainly responsible for SILC is the neutral hydrogen bridge trap, Si-H-Si. These traps may be connected with RILC in that ionizing radiation can release H from other sites, and this hydrogen may migrate and form neutral bridge traps within the oxide [17]. A similar defect may contribute to low-frequency noise in MOS transistors [18].

III. Experimental Results

In our experiment, we used samples with a Si (100) substrate and an initial SiO_2 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 film [10], [12]. A Ti:sapphire laser was used for both electron injection and as a probe of interfacial electric field.

The laser operated at 800 nm (1.55 eV) with 150-fs pulses, a repetition rate of 76 MHz, and an average power of 250 mW with a spot size diameter of 50 μm. One half of the variable thickness Si/SiO_2 sample was irradiated to a 20-Mrad(SiO_2) total dose with 10-keV X-rays at a dose rate of ~ 1 krad(SiO_2)/s. The other half of the film was masked with lead so that it was not irradiated, and it served as a control.

The experimental procedure used in our studies is as follows (see Fig. 2):

1) Initially, the shutter is open, allowing all laser pulses to be incident on the sample. In this mode, when pulses induce the laser injection of electrons from the Si into the oxide, we observe a rapid increase in the SHG signal due to an increase in the interfacial electric field [Figs. (2b), (3a), (4a)]. This occurs because some of the injected electrons are trapped at the oxide surface, giving rise to a time-dependent electric field at the interface. The electron injection from the Si into the oxide is a three-photon process because the difference between the Si valence band and SiO_2 conduction mobility band is approximately 4.3 eV (1.1 eV is the Si band gap, and the barrier height for electrons for be excited from the Si conduction band to the SiO_2 conduction band is $\sim$3.2 eV). In this case, with the

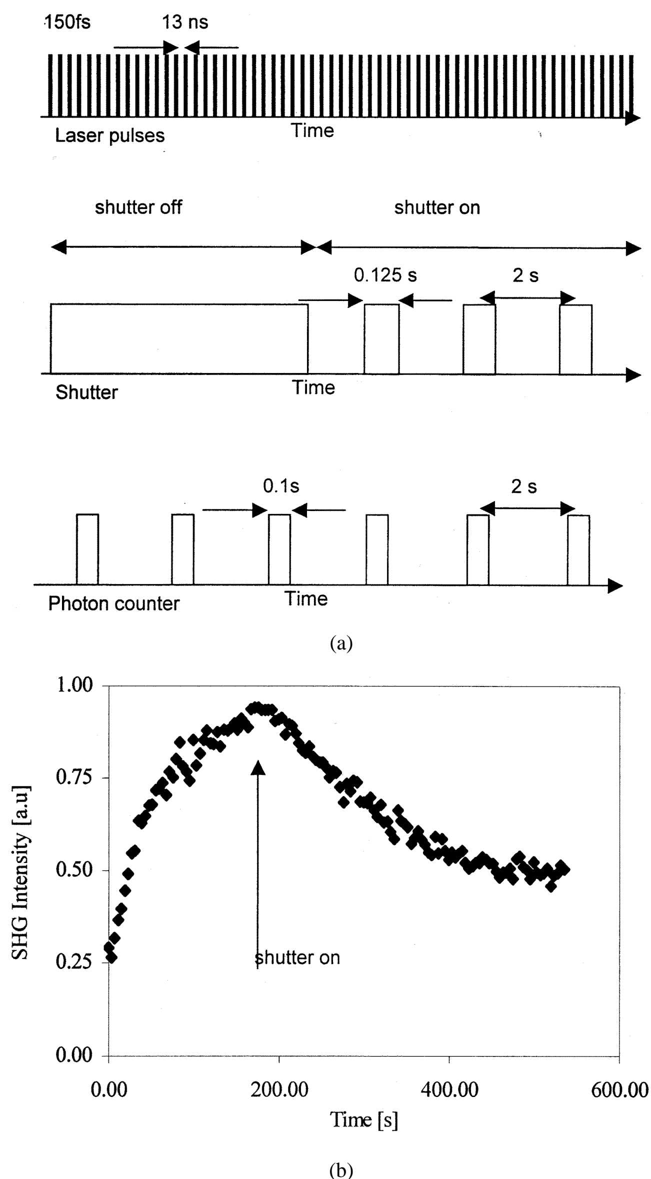

Fig. 2 Experimental procedure. (a) Laser pulse timing diagram; (b) time-dependent SHG signal from Si/SO$_2$ (6.0 nm) taken 20 minutes after irradiation to 20 Mrad (SiO$_2$)

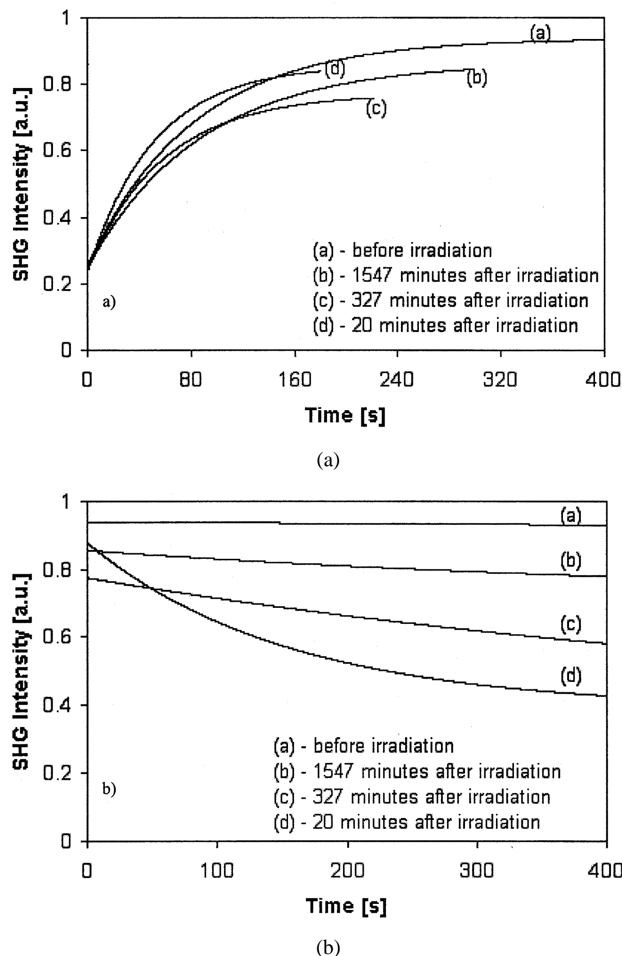

Fig. 3 Exponential fits of time-dependent SHG signals from the thick part of the oxide layer: (a) The time-dependent SHG signal due to electron injection and trapping; (b) the time-dependent decrease of the SHG signal due to recombination of carriers.

shutter open, the time-dependent function $F(t)$ is equal to unity.

2) After the signal approaches the saturation level, we turn on a shutter operating at 0.5 Hz. In this mode, the shutter is open 1/8 s for every 2 s, thus decreasing the number of pulses incident on the sample by a factor of 16. This results in a substantial decrease in electron injection into the oxide, giving rise to a negligible contribution to any increase in the electric field [Figs. (2b), (3b), and (4b)]. In this case, the laser function $F(t)$ is set to zero. As we shall see, the signal, which is a measure of the electric field at the interface, may decrease over time due to tunneling through the thin sample (less than 3 nm) and/or trap-assisted processes in irradiated samples.

Fig. 3 represents the data from the thick part of the oxide layer of the sample (approximately 6.0 nm). On the unirradiated sample, the SHG intensity rose to a steady-state level [Fig. 3(a), curve a], and after the beam average power was decreased (by turning on the shutter), the signal remained at the same level, indicating minimal electron-hole recombination at the interface [Fig. 3(b), curve a]. In contrast, on the X-ray irradiated portion of the sample [Fig. 3(a), curves b–d], after we decreased the average beam power, the signal decreased significantly [Fig. 3(b), curves b–d], indicating an increase in electron transport from the free surface back to the substrate. Hence, the X-ray radiation-induced defects in the SiO_2 are seen to greatly enhance conduction current through these thin oxides [4], [13]. In Fig. 3(b), we observe that, after a significant length of time, the response of the irradiated oxides approaches the preirradiation behavior. Thus, the particular defects causing the "extra" radiation-induced electron transport are clearly metastable.

Fig. 4 shows the results of measurements performed on a thin part of the sample (approximately 1.0 nm). On the unirradiated part of the sample, we saw an increase in the signal at high average laser power to a saturation level [Fig. 4(a), curve a]. On the X-ray irradiated thin portion of the sample, this saturation level was observed to be much lower [Fig. 4(a), curves b–d]. When the average laser power was decreased, we observed a reduction in the interfacial electric field due to tunneling in both the unirradiated and irradiated thin-oxide samples [Fig. 4(b)]. The rate

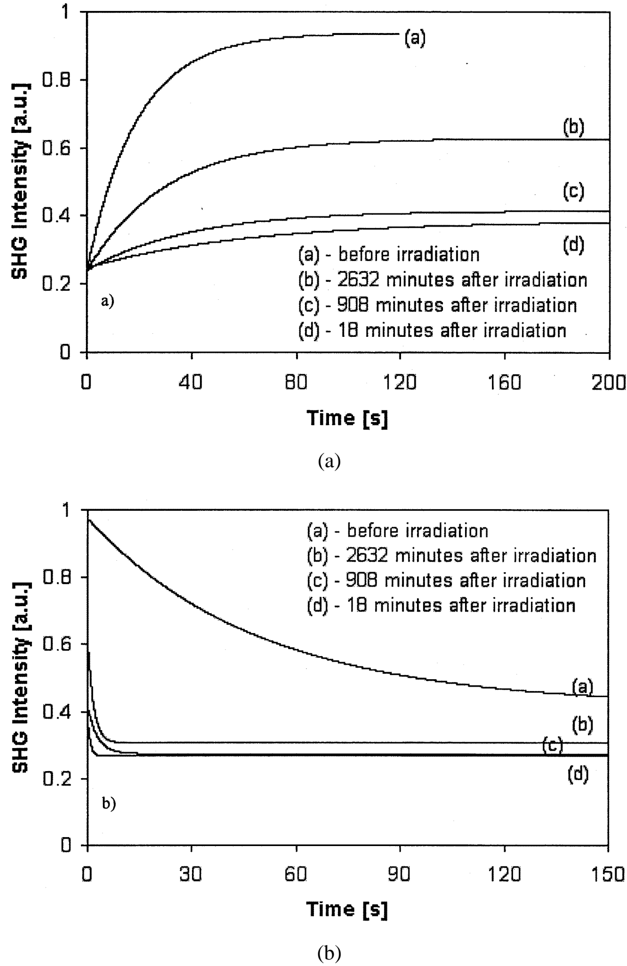

Fig. 4 Exponential fits of time-dependent SHG signals from the thin part of the oxide layer: (a) The time-dependent SHG signal due to electron injection and trapping; (b) the time-dependent decrease of the SHG signal due to recombination of carriers.

of decrease in the photo-induced electric field was substantially faster in the irradiated portion of the sample [Fig. 4(b), curves b–d] than in the unirradiated portion of the sample. These data from the thin part of the sample differ from the thick sample results in two significant ways. The SHG signals for the irradiated thin sample decayed significantly faster than the unirradiated thin sample, and the recovery rate as a function of time due to room temperature annealing for the thin samples was much slower than in the thick sample case.

IV. Discussion

The experimental results described above are associated with the transport of photo-excited electrons (excited primarily through multiphoton absorption) through the oxide, and their subsequent trapping in oxide bulk and on the free oxide surface. Once electrons are trapped at the free oxide surface, the carriers may tunnel back into the bulk if the oxide layer is sufficiently thin or if the sample is X-ray damaged. A decrease in the number of trapped electrons changes the electric field across the oxide, which results in a decrease in the EFISH signal. After X-ray irradiation, we detect a time-dependent decrease of the electric field across the oxide. We attribute this decrease in electric field to trap-assisted tunneling.

The buildup of electric field may be understood in terms of carrier transport. The electric field in (1), $E(t)$, is related to the time-dependent oxide surface charge density. The main time-dependent contribution to oxide charge density comes from surface or bulk oxide electronic traps. These processes are described by the following rate equation:

$$\frac{dn_e(t)}{dt} = F(t)\frac{n_{0e} - n_e}{\tau_{\text{trap}}} - \frac{n_e}{\tau_{\text{detrap}}} \tag{2}$$

where n_e is the density of filled electronic surface traps; n_{0e} is the density of electron surface traps, which we assume are initially completely unfilled; $1/\tau_{trap}$ gives the rate of the trap filling process (related to rate of injection, transport, and trapping); τ_{detrap} is the charge dissipation time due to tunneling and subsequent recombination with holes at the interface [4]; and $F(t)$ *is* the time-dependent function that equals 1 in the first experimental mode (shutter not blocking the laser beam) and 0 in second experimental mode (shutter blocking the laser beam).

The saturation observed during the time interval when the shutter does not block the laser may be attributed to a balance between trapping of photo-injected electrons and detrapping followed by transport back to the substrate. However, when the shutter blocks the beam, detrapping of these trapped carrier results in a decrease of the electric field and a corresponding decrease in the SHG signal. The detrapping rate τ_{detrap} primarily governs the characteristics of the fall in the SHG signal. For relatively thick oxides, detrapping of electrons is low due to a reduced tunneling probability, relatively to the thinner oxide, which causes the SHG to fall slowly compared with the thin oxide case.

The SHG data from the thin oxide ($\sim$1-nm) region exhibit two very interesting features, as shown in Fig. 4. Before irradiation, the thinner oxide shows a markedly enhanced tunneling (recombination) rate in comparison with the thick oxide case, as expected. After X-ray irradiation, the tunneling rate is drastically increased and does not significantly change over the time frame of the observation. These results show that SHG measurements can efficiently detect the presence of traps capable of enhancing charge transport rates in irradiated SiO_2. However, it is difficult to compare these results quantitatively with electrical measurements because, if one puts a gate on these oxides, the surface states that capture the electrons, which lead to the EFISH signal in these devices, are either modified or eliminated. Nevertheless, that one is able to sense the presence and the time dependence of these defects with the simple optical measurements suggests that one may be able to adapt this technique as a method of in situ monitoring of the quality of thin dielectric layers.

V. Conclusion

In this work, we have demonstrated that optical second-harmonic generation, which is contactless and nondestructive, is a 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. These measurements can provide information about the injection, trapping, detrapping, transport, and recombination processes in thin layers of SiO_2 on Si that are difficult or impossible to obtain from conventional electrical measurements. Some of the defects facilitating electron transport in these oxides can be annealed fairly quickly at room temperature. The nature of these defects is unknown; however, in prior studies of electrical RILC, it has been suggested that O vacancies (E' centers) or hydrogen-related defects may play a strong role in this process. This work shows the utility of SHG measurements in evaluating defect properties in ultra-thin SiO_2 layers, as well as the potential impact of these defects on device radiation response.

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