Spin/carrier dynamics at semiconductor interfaces using intense, tunable, ultra-fast lasers


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We review recent advances in spin/carrier dynamics at semiconductor interfaces using intense, tunable, ultrafast lasers, involving (a) carrier dynamics at Si/SiO2 interfaces with different oxide thicknesses, (b) radiation enhanced electron transport in ultra-thin oxides, and (c) ultrafast spin dynamics in semiconductor heterostructures, probed by second-harmonic generation (SHG).

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1 Introduction

Second Harmonic Generation (SHG) has been shown to be an effective technique for characterizing carrier and spin dynamics at semiconductor interfaces. In particular, we have developed a contactless two-color optical technique that allows us to monitor carrier transport (injection, tunneling) by multiphoton internal-photoemission induced second-harmonic generation. We have used this technique to measure the Si/SiO2 band-offset. One- and two-photon internal-photoemission thresholds were measured to be 4.5 eV and 2.25 eV respectively. In addition, we applied this technique to measure X-ray irradiation enhanced electron transport across thin oxides Si/SiO2 samples. Measured electron transport rates across an irradiated oxide were found to be substantially higher in comparison to unirradiated oxides. This effect is attributed to the presence of X-ray irradiation induced defects that act as intermediate trapping sites facilitating enhanced electron tunneling through the oxide. Finally, we report the application of pump–probe second harmonic generation to monitor spin dynamics in nonmagnetic semiconductor heterostructures. Spin-polarized electrons were selectively excited by a pump beam in the GaAs layer of GaAs/GaSb/InAs structures. However, the induced magnetization manifests itself through the SHG probe signal from the GaSb/InAs interface, thus indicating a spin-polarized electron transport. We find that the magnetization dynamics is governed by interplay between the spin density evolution at the interfaces and the spin relaxation.

2 SHG studies of silicon interfaces

Second-harmonic generation has proved itself to be a novel, nondestructive probe of Si/oxide interfaces [1]. We have developed a contactless two-color optical technique that allows us to monitor carrier trans-
port (injection, tunneling) processes at Si/oxide interfaces [2]. This method involves two steps: (1) optically stimulated electron injection into the oxide by a high intensity pump laser and (2) detection of transport, trapping and recombination rates using time-dependent electric-field induced second-harmonic generation arising from charge separation at the interface by a less intense probe laser. A pump beam from tunable Optical Parametric Generator (1–6 eV) is used to inject carriers at different power and photon energy. A probe beam from Ti:sapphire laser at 800 nm with low intensity is used to monitor the time-dependent electric field via SHG. The radiated SH intensity can be described by

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

where \( I^{\omega} \) and \( I_{2\omega}(t) \) are the intensities of the fundamental and the time-dependent SHG beams, \( \chi^{(3)} \) is the third-order nonlinear susceptibility, \( \chi^{(3)} \) is the effective second-order susceptibility and \( E(t) \) is an interface electric field. The quasistatic electric field in Eq. (1) is proportional to the density of charged surface electron traps, which can be given through the solution of the rate equation:

\[ \frac{dn_e}{dt} = \left( n_{ne} - n_e \right)/\tau_{\text{PUMP}} + \left( n_{ne} - n_e \right)/\tau_{\text{PROBE}} - n_e/\tau_{\text{detrapping}}, \]

where \( n_{ne} \) describes the initial number of unfilled electronic traps, \( 1/\tau_{\text{PUMP}} \) and \( 1/\tau_{\text{PROBE}} \) give the rates of filling up the surface electronic trap states due to the pump and probe beams (the second one is negligible). \( \tau_{\text{detrapping}} \) characterizes lifetime of surface electronic trap states; it contains contributions from the rate describing the detrapping of surface electrons, the tunneling rate through the oxide and their recombination with holes at the interface.

### 2.1 Band offset studies of Si/SiO\(_2\) interfaces

We apply the two-color technique, involving time-dependent EFISH combined with a tunable laser source for carrier injection, to determine band offsets at semiconductor interfaces [2]. One sample studied was a conventional, thermally grown 42 Å thick SiO\(_2\) deposited on Si(100) by Lucent Technologies. At this oxide thickness, the injected electrons reach the surface with a high probability, giving rise to a large field and therefore to a large easily detectable time-dependent SHG signal [3]. This oxide is also thick enough that electron tunneling from the surface back to the interface is negligible [4]. We found that \( \tau_{\text{detrapping}} \) is of the order of several hours for a ~40 Å oxide. This is not significant under the timescale of our experiment. Since \( 1/\tau_{\text{PUMP}} \) is significantly greater then the other two rate constants in Eq. (2), the solution can be easily found:

\[ n_e(t) = n_{ne} \left( 1 - e^{-t/\tau_{\text{PUMP}}} \right). \]

Therefore our time-dependent EFISH data can be fitted by

\[ F^{2\omega} = |\psi_0 + a (1 - e^{-t/\tau_{\text{detrapping}}})|^2, \]

where \( \psi_0 \) and \( a \) are phenomenological values related to the initial and saturation SHG levels.

Figure 1a shows typical example of a time-dependent pump–probe type SHG measurement taken on our 42 Å thick Si/SiO\(_2\) sample. When the injection beam was turned on, the signal rose rapidly indicating the creation of a time-dependent quasistatic electric field. This field originates from charge separation across the interface due to trapping of injected electrons at the oxide surface by the ambient oxygen, while the holes remain in the Si. After a steady-state signal was reached, we blocked the injection beam and observed that the signal remained constant. This is in contrast with our observations on a 17 Å sample (Fig. 1b). For this ultrathin sample case, when we blocked the pump beam, the SHG signal was observed to slowly decrease in intensity indicating an increasingly lessened electric field across the interface. This observation may be explained by noting for oxide thicknesses below a critical value (~30 Å), electron tunneling rates become significant, leading to faster detrapping from the O\(_2\)-rich surface and subsequent recombination with holes at the interface.
Fig. 1  a) Two-color type time-dependent SHG data taken on a 42 Å thick oxide sample compared to b) data taken on a 17 Å sample. After the pump laser is turned off the SHG signal decreases for the thinner sample, indicating that electrons tunnel back to the interface.

Figure 2a shows the SHG signal measured for different pump beam intensities, at the same wavelength 516 nm (2.4 eV). As the injection beam intensity increases the SH signal reaches the saturation level at an earlier time indicating an enhancement in the injection rate.

We have determined 1/$\tau_{\text{PUMP}}$ for a large range of incident pump beam intensities at several different wavelengths between 258 nm and 663 nm. Fitting dependence of 1/$\tau_{\text{PUMP}}$ rate on the pump laser intensity gives a slope, which we associate with the number of photons required in the injection given wavelength. Figure 2b shows the dependence of 1/$\tau_{\text{PUMP}}$ rate constants on the pump laser intensity at 516 nm. Fitting this intensity dependent data to 1/$\tau_{\text{PUMP}}$ $\propto$ (I$_{\text{PUMP}}$)$^{n}$ gives a slope of 2.26 ± 0.10, which we associate with the number of photons required in the injection process at 516 nm (2.4 eV). Here we assumed that the measured trap-filling rate (1/$\tau_{\text{PUMP}}$) is proportional to the probability of the n-photon interband transition given by [5],

\[ W_n = K_n f^{(n)}(\omega) / (n\hbar\omega), \]

where $K_n$ is the n-photon absorption coefficient, $f^{(n)}$ is the incident beam intensity at energy $\hbar\omega$.

The number of photons required to inject electrons from silicon to SiO$_2$ was determined for several different energies in a range of pump photon energies (1.9–4.8 eV) (Fig. 3). We observe the stepwise jumps from one- to two-photon (between 4.56 and 4.50 eV) and then from two- to three-photon (between 2.30 and 2.20 eV) processes, as the incident pump energy decreases. The energies for stepwise jumps are
identified as the thresholds for one-photon (~4.53 eV) and two-photon (~2.25 eV) electron injection from Si valence band into SiO$_2$ conduction band. To our best knowledge this is the first time when multiphoton internal photoemission thresholds were observed.

Published values for the Si(VB)-SiO$_2$ (CB) offset are generally in the 4.05–4.6 eV [6, 7] range. The wide variation is mostly attributed to excitations to overlapping excitonic levels with the SiO$_2$ conduction band. Measured thresholds in internal photoemission (IPE) [8] studies are in the range of 4.05–4.35 eV [6], where the lower end of the range is attributed to mobile ion contamination in the oxide. IPE measurements are generally performed on MOS structures, where the oxide thickness is in the order of 1 µm. In a recent study Afanasev et al. found that the Si(100)(VB)–SiO$_2$ (CB) barrier of 4.25 eV is unchanged down to oxide thicknesses of ~10 Å (IPE) [9]. A recent experimental study by the Lucovsky’s group determined 4.35 eV for the Si(100)(VB)–SiO$_2$(VB) offset via X-ray photoemission method [10]. This gives 4.6 eV for Si(VB)–SiO$_2$(CB) difference if one uses 8.95 eV for SiO$_2$ bandgap.

2.2 Two-color optical technique for characterization of X-ray radiation enhanced electron transport in SiO$_2$

Carrier movement (injection, transport, tunneling, recombination) and charge trapping in gate oxides are essential factors in understanding semiconductor device performance and degradation, especially in a radiation environment. In addition to the population of precursor defects with trapped charge and the possible generation of new traps, X-ray irradiation also may influence the carrier dynamics at interfaces. It has been shown recently that high doses of ionizing radiation in thin oxides (40–60 Å) may cause Radiation Induced Leakage Current (RILC) [11]. The conduction mechanism in RILC (as well as in Stress Induced Leakage Current, SILC) has been attributed to neutral oxide defects, which mediate electron tunneling across the oxide [12].

Presently, characterization of radiation damage in Si/SiO$_2$ systems is usually accomplished with electrical methods such as capacitance–voltage ($C$–$V$) and current–voltage ($I$–$V$) measurements. We use a novel two-color technique, based on time-dependent electric field induced SHG, for direct measurements of changes in electron transport characteristics due to X-ray irradiation in thin oxides to characterize the radiation response of a 42 Å SiO$_2$ film on Si(100) [13]. We find that the detrapping rate of surface charge in the X-ray irradiated devices is much higher than that of unirradiated devices.

The samples were cut from a wafer of thermally grown 42 Å SiO$_2$ film on Si(100) produced by Lucent Technologies. The irradiation was carried out with a 10-keV X-ray source, at a dose rate of ~1 krad(SiO$_2$)/s. Since the samples had no gate, they were irradiated without electrical bias.

The following experimental procedure was used in the measurements presented here:

(1) Initially the pump laser was off and the probe laser measured a constant background SH signal from the sample. After turning on the pump beam, a fast rise in the probe signal was observed, indicating that electrons were injected into the oxide, transported to the surface and trapped by the ambient surface oxygen. The holes remained at the interface thus resulting in an electric field arising from charge separation. The solution of Eq. (2) is an exponential rise to a maximum which under the conditions of
\[ \frac{1}{\tau_{\text{PUMP}}} > 1 / \tau_{\text{PROBE}}, \quad \frac{1}{\tau_{\text{detrapp}}} \]

becomes

\[ n_e(t) = n_{0e}(1 - \exp(-t/\tau_{\text{PUMP}})). \]  \hspace{1cm} (6)

(2) After the signal reached a saturation level, the pump beam was blocked and the probe SHG signal decreased. In this case, the surface trapped electrons transported back to the interface to recombine with the holes remaining at the interface. Since now \( 1 / \tau_{\text{PUMP}} = 0 \) and \( 1 / \tau_{\text{detrapp}} \gg 1 / \tau_{\text{PROBE}} \) only the third term in Eq. (2) is present, and the solution becomes a simple exponential decay for \( n_e(t) \): \[ n_e(t) = n_{0e} \exp(-t/\tau_{\text{detrapp}}). \]  \hspace{1cm} (7)

Figure 4 compares time-dependent pump–probe type EFISH measurements performed on irradiated [15 Mrad(SiO\(_2\))] and non-irradiated Si/SiO\(_2\) samples with 42 Å oxides. Electron tunneling across a non-irradiated oxide at this thickness has a very low probability; it only becomes significant below thicknesses of ~30 Å [14]. In both irradiated and non-irradiated samples the electric field increases rapidly after the pump laser is turned on. For the non-irradiated sample the EFISH signal stays at a constant saturation level after the pump laser is blocked, indicating that the electrons in the surface traps have a long lifetime. In contrast, the electric field across the X-ray irradiated sample decreases steadily, implying that the trapped electrons tunnel back to the interface and recombine with the holes, thereby decreasing the electric field. This suggests that the X-ray irradiation increases the rate of electron transport through the oxide. Systematic dose dependent measurements were not carried out on these samples, but we have seen similar time-dependent behavior (shown in Fig. 4) for similar samples irradiated up to 2 Mrad(SiO\(_2\)) and also 20 Mrad(SiO\(_2\)) doses via a 10 keV X-ray source.

We have also studied the long-term time dependence of the observed leakage in our X-ray irradiated samples at a dose of 20 Mrad(SiO\(_2\)). Figure 5 shows the \( 1/\tau_{\text{detrapp}} \) (Eq. (7)) values (presumably associated with trap-assisted tunneling rates) deduced from our measurements versus time after irradiation. The figure depicts that the rate at which the electrons tunnel back to the interface decreases with time after X-ray irradiation. These rates were several orders of magnitude lower 2–3 days after irradiation. We suggested that the defects mediating the electron transport across the oxide may anneal at room temperature. In our experiments the OPA pump laser should not give rise to any significant heating due to its low repetition rate. In addition, we reduced the duty factor of this laser to 1/8\(^{th}\) using a shutter. Also, each data point was taken on a fresh spot on the sample, at least 500 µm away from the previous measurement.

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**Fig. 4** Two-color EFISH measurements comparing X-ray irradiated and non-irradiated samples. After the pump laser is blocked the SH intensity steadily decreases for the irradiated sample indicating that electrons are tunneling from the surface of the oxide back to the interface.

**Fig. 5** Measured detrapping rates on fresh spots on a 42 Å oxide as a function of time past after X-ray irradiation up to 20 Mrad dose. The inset shows an example of an exponential decay fit for obtaining detrapping rates.
point. With these precautions, we believe laser-heating induced annealing should not be a significant factor in these experiments.

One way of finding out whether our laser itself gives rise to the observed decrease in the electron tunneling rate with time is to perform consecutive measurements on the same laser spot. We irradiated the same spot several times on the sample with the pump laser after the probe signal reached a minimum steady-state level, measured the tunneling rates versus time after irradiation, and compares it with measurements taken on fresh sample spots. The continued irradiation by the pump laser on the same spot enhances the decrease in the observed X-ray irradiation effect probably by altering the concentration of irradiation-induced trapping sites.

There are two possible mechanisms to account for our observations of pump-laser-induced reduction of the radiation effect. The first is optically induced local healing of the defect responsible for the leakage in X-ray irradiated samples. Since the laser peak intensities are high and multiphoton processes are possible, the pump laser may break bonds at the defect sites (such as the H-bridge site) and lead to the local relaxation of the structure and consequent removal of the defect.

3 Ultrafast spin dynamics in GaAs/GaSb/InAs heterostructures probed by SHG

Ultrafast spin-sensitive spectroscopy provides unique information about spin relaxation in semiconductor heterostructures as well as spin-polarized electron transport across interfaces [15, 16]. Knowledge of the processes governing spin dynamics is essential for designing novel multifunctional electronic and optoelectronic devices, including base components for quantum computing [17]. Among the wide variety of multilayer semiconductors, GaSb/InAs heterostructures are especially promising [18].

The excitation of an ensemble of spins by a circularly polarized laser light tuned just above the band gap gives rise to a net magnetization. The typical time-resolved techniques, such as polarized photoluminescence spectroscopy [19, 20], pump–probe transmission/reflection [21–24], and Faraday or Kerr rotation [17, 25], all rely on the linear response of the spin subsystem to a probing light, and are well suited for monitoring dynamics in the bulk of semiconductor structures. On other hand, the nonlinear optical effects, such as SHG, are known to be highly sensitive to local magnetic fields occurring at magnetized surfaces at interfaces in magnetic-semiconductor-based multilayers [26]. Therefore, the application of SHG in the pump–probe configuration is a promising method for studying the dynamics of optically excited spins at the semiconductor interfaces.

We apply the pump–probe SHG technique to study ultrafast spin dynamics in nonmagnetic heterostructures. Spin-polarized electrons were selectively excited in the GaAs layer of GaAs/GaSb and GaAs/GaSb/InAs heterostructures. Only the GaAs/GaSb/InAs samples showed a significant induced magnetization indicating interlayer spin-polarized electron transport from GaAs to InAs. The dominant contribution to the magnetic-field induced SHG signal results from high local density of spins accumulated at the semi-metallic GaSb/InAs interface. Temperature dependence of induced SHG signals in the range from 4.3 to 300 K revealed two distinct mechanisms governing magnetization dynamics: the evolution of the local spin density at the interfaces and the spin relaxation.

We have investigated two heterostructures grown by molecular beam epitaxy: (1) GaAs(100 nm)/GaSb(400 nm) and (2) GaAs(100 nm)/GaSb(500 nm)/InAs(20 nm). The initial beam of 150 fs pulses from a mode-locked Ti : Al₂O₃ laser (Mira 900) at the wavelength of 800 nm (1.55 eV) and a repetition rate of 76 MHz was split into pump and probe beams. The probe beam of 120 mW average power has passed through an optical delay stage. The pump beam was chopped at a frequency of 400 Hz and, after that, had the same average power. The overlap spot of the pump and probe beams on the sample was ~100 μm in diameter. The pump beam was incident normally on the sample with either left or right-handed circular polarization (σ⁺ or σ⁻, respectively). The probe beam was linearly polarized (p or s), and directed to the sample surface at the angle of 75°. The pump-induced SHG signal was monitored as a function of probe-to-pump delay times. Note that only p linearly polarized probe light contributes to the induced signal, similarly as that for SHG measurements of magnetized surfaces is typically observed.
The SHG signal was optically separated from the reflected fundamental probe beam and measured by a photomultiplier tube through a “lock-in” amplifier triggered by chopped pump pulses.

Figure 6 shows the pump-induced SHG signals taken on GaAs/GaSb heterostructure (sample 1) at a temperature $T = 4.3$ K. No significant difference was observed between signals measured with $\sigma^+$ or $\sigma^-$ polarized pump light [Figs. 6a and 6b, respectively], indicating that the signal is due to the induced electric field at the interface. The interfacial electric fields caused by charge separation between photoexcited carriers are known to strongly enhance the SHG response [28]. The measured signal was fitted by a combined exponential rise/decay function. The signal intensity increases with a time constant of $\tau_R \approx 3$ ps, followed by a decay with $\tau_D \approx 100$ ps. The induced signal completely disappears at room temperature [Fig. 6a].

The induced SHG signal from GaAs/GaSb/InAs samples is shown in Fig. 7a. A new striking feature is a long-lived $\tau_{R2} \approx 15$ ps rise-time component, which results in a shift of the signal peak towards longer times with respect to those for the GaAs/GaSb samples. Moreover, the SHG signal intensities for $\sigma^+$ and $\sigma^-$...
σ+ pump polarizations are different, indicating an induced magnetization, which we ascribe to the presence of spin-polarized electrons in the InAs layer. Since the spins were excited in the GaAs layer, this indicates an interlayer spin-polarized electron transport. Correspondingly, the long-lived $\tau_{22} \sim 15$ ps rise-time component characterizes the rate of spin transfer to the InAs layer.

Retaining only linear terms in the induced electric field, $\delta(t)$, and magnetic field, $M(t)$, the nonlinear pump–probe polarization can be presented as [26, 28],

$$P_{\pm}^{nl}(2\omega,t) = \left[ \chi^{(2)} + \chi^{(3)} + \chi^{(3)} M(t) \right] E(\omega) t^2,$$

(8)

where $E(\omega)$ is the electric field component of the incident probe light, and $\chi^{(2)}$, $\chi^{(3)}$, and $\chi^{(3)}$, are the corresponding nonlinear susceptibilities. The alternate signs in Eq. (8) indicate two possible directions of the induced magnetic field normal to the interface. The magnetic- and electric-field induced contributions were then extracted from the pump induced SHG signal intensity, $\Delta I^{(2\omega)}(t)$ as

$$\Delta I^{(2\omega)} - \Delta I^{(2\omega)} \propto M(t), \quad \Delta I^{(2\omega)} + \Delta I^{(2\omega)} \propto \delta(t).$$

(9)

Figure 7b shows the extracted induced magnetization for GaAs/GaSb/InAs heterostructure, whereas the extracted electric-field-induced signal closely follows that for the GaAs/GaSb sample.

Because the laser light was tuned just above the GaAs band gap, spin-polarized electrons excited in the smaller band gap GaSb and InAs layers are much more energetic (0.74 and 1.11 eV, respectively) and lose their spin polarization as they relax to lower energy states [30]. These unpolarized electrons accumulate in the GaAs and InAs regions while the holes are amassed in the GaSb layer. The resulting charge separation at the interfaces [inset in Fig. 6b] gives rise to the interfacial electric fields resulting in the initial growth of the SHG signal (~2 ps at 4.3 K). This rise time decreases to ~300 fs for $T \sim 250$ K, matching the typical room temperature values for carrier thermalization [21–23]. The induced electric fields at the interfaces bend the initial energy profile and lower the barrier at the GaAs/GaSb interface [inset in Fig. 7b]. A subsequent relaxation of the interfacial electric fields manifests itself as the $\tau_{0} \sim 100$ ps decay of the induced SHG signal [30]. The appearance of longer decay time in Fig. 7a originates from constant background due to a residual electric field at the GaSb/InAs interface. This background is present only in the GaAs/GaSb/InAs sample and reflects the semimetallic nature of the GaSb/InAs interface which does not fully “unbend” as the induced interfacial fields relax. The 100 ps decay-time constant (common for both samples) for interfacial electric fields is obtained after extracting this constant background. Importantly, the interfacial electric fields are known to be much stronger at the semimetallic GaSb/InAs interface as compared those at the GaAs/GaSb interface [18]. This leads to higher local spin density at the GaSb/InAs interface and, hence, to significant induced magnetization in the GaAs/GaSb/InAs sample.

The temperature dependence of the peak intensity for the GaAs/GaSb sample exhibits a sharp decrease in the range of 4.3–100 K, while for the GaAs/GaSb/InAs sample, the signal first grows and then stabilizes [Figs. 6c and 7c]. We attribute this behavior to thermally activated electrons in GaAs overcoming the interfacial barrier. In the GaAs/GaSb/InAs sample, the initial signal increase is attributed to the arrival of additional spins at the GaSb/InAs interface. Note that electrons with uncompensated spin in GaAs are activated first since they occupy states with higher energies. Subsequent signal stabilization in the range from 50 to 100 K is due to the competing process involving a decrease in the interfacial electric field as the unpolarized electrons begin to pass through the barrier. Further intensity decrease in the range from 100 to 300 K indicates a weakening of the interfacial fields as the electron wave functions become more extended, effectively reducing the carrier density at the interface. Note that the induced signal in GaAs/GaSb samples shows a plateau in the range from 100 to 170 K, which we attribute to the thermal activation of electrons previously trapped at the impurity centers in bulk GaAs.

The temperature dependence of decay-time constants is similar for both samples in the range from 4.3 to 180 K [Figs. 6c and 7c] staying at $\tau_{0} \sim 100$ ps. At higher temperatures, however, $\tau_{0}$ decreases as $T^3$ for the GaAs/GaSb/InAs sample, while remaining unchanged for the GaAs/GaSb sample. The $T^3$ dependence is consistent with Dyakonov–Perel (DP) mechanism [29], and the measured room temperature
value $\tau_0 \sim 20$ ps matches that in InAs measured previously using pump–probe spectroscopy [24]. Note, however, the DP mechanism is expected to dominate for temperatures down to $\sim$50 K. The regime change at $T \sim 180$ K indicates a crossover to interface dominated dynamics. As the electric field at the GaSb/InAs interface relaxes, the time evolution of spin density follows that of charge density, leading to a reduction of the magnetic-field-induced SHG signal.

### 4 Summary

In this paper, we review recent advances in spin/carrier dynamics at semiconductor interfaces using intense, tunable, ultrafast lasers, including carrier dynamics at Si/SiO$_2$ interfaces, radiation enhanced electron transport in ultra-thin oxides, and ultrafast spin dynamics in semiconductor heterostructures, probed by SHG. We have made first measurements of the Si valence to SiO$_2$ conduction band offset via multiphoton internal-photoemission induced second-harmonic generation. We have showed that multiphoton internal-photoemission induced second-harmonic generation promises to become a valuable experimental tool in determining band offsets in wide variety of semiconductor interfaces including many new alternate and chemically modified oxides under investigation. This novel contactless technique can be easily applied for most systems where the two materials in contact are isotropic or amorphous. We determined that the electron-tunneling rate decreases with time at room temperature after X-ray irradiation, indicating that the electron transport-mediating traps may be annealed at room temperature. This is in contrast with annealing studies performed at substantially higher temperatures on RILC, suggesting that the defects responsible for the Laser Interrogated Leakage Current (LILC) observed in our experiments are either (1) defect precursors (observable at lower dosages due to increased sensitivity), or (2) different than, the defects responsible for RILC. It is likely these defects are O vacancies ($E'$ centers) or hydrogen-related. Pump–probe SHG measurements for nonmagnetic GaAs/GaSb/InAs semiconductor heterostructures revealed interlayer spin-polarized electron transport. We found that the optically induced magnetization dynamics in such structures originates from two distinct sources: one of them related to the evolution of the local spin density at the interfaces, and the other one arising from the spin relaxation. The extreme sensitivity of the SHG to the interfacial fields, which allowed us to distinguish between these two mechanisms, makes it a unique tool for studying the spin and carrier dynamics in multilayer semiconductors.

### References


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