High-speed electrical sampling using optical second-harmonic generation

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We report the application of optical second-harmonic generation to the measurement of ultrafast electrical pulses. The technique relies on the sensitivity of the second-harmonic response to electric fields in centrosymmetric materials. Electrical pulses propagating on a silicon-based coplanar transmission line have been characterized with subpicosecond time resolution and $100 \text{ mV}/\sqrt{\text{Hz}}$ sensitivity. We have measured the bias dependence of the second harmonic intensity over a 20 V range and have used this data to calibrate the transient response. The observed full-width at half maximum response time of the SHG waveform is ~1 ps, which is consistent with the value obtained from an electronic cross-correlation measurement. © *1996 American Institute of Physics.* [S0003-6951(96)03832-6]

The rapid progress in high speed electronic devices has created the demand for new measurement technologies. For maximum utility, these techniques must exhibit wide bandwidth, accurate signal reproduction, and minimal loading. In response to this need, several ultrafast optoelectronic techniques have been developed.[1] The first approach involved the fabrication of photoconductively gated switches within the device of interest.[2] A number of other measurement methodologies including electro-optic sampling,[3] photoemissive sampling,[4] and charge-sheet probing[5] have also been devised. Electro-optic sampling has received particular attention since it is capable of providing picosecond temporal resolution and submillivolt sensitivity. In the case of GaAs, the electro-optic properties of the substrate itself may be exploited to perform *in situ* measurements.[6] However, since the dominant electronic material, silicon does not exhibit a linear electro-optic effect, an external probe is necessary.

Optical second harmonic generation (SHG) has been shown to be an effective tool for studying surfaces of centrosymmetric media.[7,8] A high degree of sensitivity to electric fields has been demonstrated in studies of semiconductors, both with fields applied normal to the surface and under the influence of naturally occurring depletion fields.[9–11] Recently, Lüpke *et al.* characterized the in-plane electric field dependence in silicon using a transmission line structure.[12] These investigations suggest the possibility of measuring *transient* electric fields in high speed silicon-based devices. In this letter, we demonstrate the first measurement of an ultrafast electrical pulse by SHG. The method does not require any external probes or crystals. In the results presented here, we have been able to detect an electrical pulse propagating on a transmission line with subpicosecond time resolution. In this approach, we expect the time resolution to be controlled by the laser pulse duration down to an inherent response time of less than 10 fs, while the spatial resolution is limited only by the focusing of the probe beam.

We fabricated a coplanar waveguide structure, shown schematically in Fig. 1, on silicon-on-sapphire. Since the probing depth in the SHG measurements is short, the 0.6 μm epitaxial silicon film may be considered equivalent to a bulk sample. Ultrafast electrical pulses are generated on the transmission line by gating the upper photoconductive gap under an applied dc bias. The SHG measurements were performed at a nearby spot in the channel region straddling the center conductor, while the electronic cross-correlation measurement required the inclusion of a second probe finger. The channel regions on each side of the center line were 10 μm wide and the photoconductive gaps were separated from one another by 30 μm. The axis of the transmission line ran parallel to the $(1\bar{1}0)$ direction of the epitaxial silicon. The structure was formed by aluminum metallization using standard techniques. In order to reduce the carrier lifetime, the device was implanted with two doses of O^+ ions, $10^{15}/\text{cm}^2$ at 100 keV followed by $10^{15}/\text{cm}^2$ at 200 keV.[13] We have found experimentally that the ion implanation step significantly improves the ohmic nature of the contacts, as demonstrated by the current voltage ($I-V$) characteristics (not shown).

The experimental arrangement is shown schematically in Fig. 2. We used a 76 MHz mode-locked Ti:sapphire laser operating at 800 nm with a pulse duration of 150 fs as the optical source. Ultrafast electrical pulses were produced by driving the upper photoconductive gap (Fig. 1) with an average optical power of up to 70 mW. The pump beam was directed onto the upper gap at normal incidence after passing through a variable delay stage. The *s*-polarized probe beam,
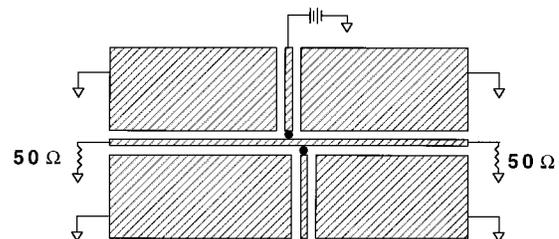

FIG. 1. Schematic drawing of the coplanar waveguide transmission line. The device consists of a center line with 10 μm wide channels on each side. The black circles show where the pump and probe beams impinge on the device.
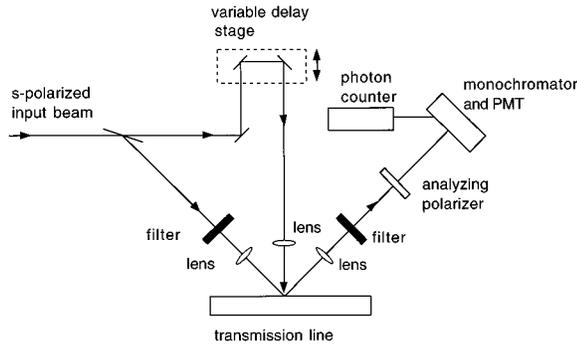
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FIG. 2. Schematic drawing of the experimental setup.

FIG. 4. The dependence of the *s*-polarized second harmonic intensity on the applied dc bias for an *s*-polarized fundamental beam. The bias is applied directly to the center conductor of the transmission line and the transient field is probed in the channel region. The data are fit to a quadratic variation of SH intensity with bias.

with an average power of up to 100 mW, was incident on the transmission line at 45° after passing through optical filters to remove any second harmonic (SH) photons. This beam was focused to a spot size of approximately 10 μm and positioned at the center of the lower channel near the pump gap. The device was oriented so that the axis of the transmission line lay in the plane of incidence of the probe beam. Thus, the *s*-polarized electric field of the probe was perpendicular to the length of the channel and parallel to the dc electric field. The reflected beam passed through several optical filters to remove the fundamental photons and an analyzing polarizer oriented to pass only *s*-polarized photons. The SH photons were dispersed by a monochromator and detected with a photomultiplier tube and photon counter.

We examined the temporal response of the device by performing an electronic cross-correlation measurement. The pump and probe gaps were each gated with an average optical power of 60 mW. The observed cross-correlation measurement with a bias of 10 V, shown in Fig. 3, has a full-width at half maximum (FWHM) of 1.55 ps. The current, i_{cc}, measured as a function of the time delay, τ, is given by[14]

$$i_{cc}(\tau) \propto \int_{-\infty}^{\infty} g(t) E_{tr}(t-\tau) dt, \qquad (1)$$

where $g(t)$ is the gating function of the probe gap and E_{tr} is the transient electric field. We note that ideally $E_{tr}(t)$ should be identical to $g(t)$, ignoring dispersion and loss. The rise time of $g(t)$ is determined by the time integral of the laser pulse and the carrier scattering time, while the decay time is related to the carrier lifetime. The magnitude of $g(t)$ is linearly proportional to the probe intensity. The asymmetry in
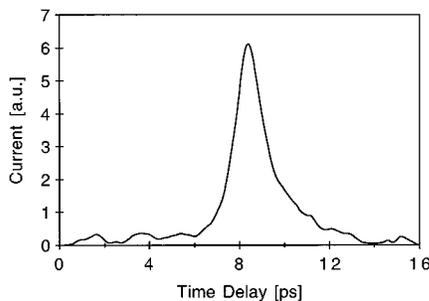

FIG. 3. The temporal waveform from a two gap electronic cross-correlation measurement. The pulsewidth is 1.55 ps (FWHM).
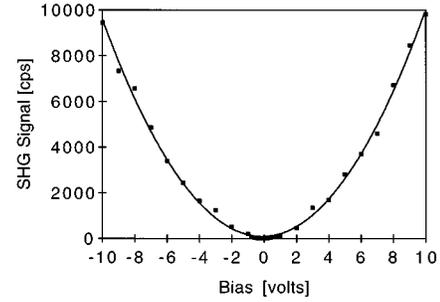
the waveform may be attributed to the dissimilar nature of the two photoconductive gaps. If we ignore the differences between the gaps, the gating width (FWHM) of a single gap may be approximated by dividing the cross-correlation width by $\sqrt{2}$[15] to obtain a value of 1.1 ps.

We initially measured the SH signal variation under the application of a *static* bias on the transmission line. Since the metal contacts to the silicon are ohmic in nature, because of the ion implantation process, the applied bias and the dc electric field scale directly with one another. The observed SH intensity versus applied bias is shown in Fig. 4. The bias dependence is fit to a parabolic form, with a vanishing minimum lying at the origin. We observed a shot noise limited minimum voltage sensitivity of ~ 100 mV/$\sqrt{\text{Hz}}$ [corresponding to a minimum electric field sensitivity of 100 (V/cm)/$\sqrt{\text{Hz}}$]. Several refinements that would significantly enhance this sensitivity are discussed below. We estimate that the average SHG power observed from the transmission line device with a 10 V bias, $\sim 10\,000$ counts per second (cps), corresponds to ~ 150 fW out of the device.

The bias dependence may be explained by considering the SH intensity at frequency 2ω, $I_{ss}^{(2\omega)}$, for *s*-polarized excitation and detection as a function of an applied dc field. If we denote the coordinate perpendicular to the plane of incidence (and the transmission line) by x, we may write[7,12]

$$I_{x,x}^{(2\omega)} \propto |\kappa \chi_{s,xxx}^{(2)} + \chi_{xxxx}^{(3)} E_x^{dc}|^2 [I_x^{(\omega)}]^2. \qquad (2)$$

In this expression, $\chi_s^{(2)}$ and $\chi^{(3)}$ are the second-order nonlinear susceptibility of the surface and the third-order nonlinear susceptibility of the bulk material, respectively. The usual bulk second-order susceptibility has been omitted, since it vanishes in centrosymmetric media such as silicon. The constant κ is determined by the optical properties of the material and the frequencies involved. For clarity, we have not explicitly included the contribution from the bulk nonlocal terms to the second-order nonlinear response in the absence of a dc field. Although an anisotropic term ξ may appear in this measurement,[7] it has, for our present purposes, a behavior analogous to that of $\chi_{s,xxx}^{(2)}$. The sensitivity of the SHG technique for probing electric fields arises from the fact that the background is due to the second-order nonlinear response of the surface and the nonlocal bulk terms only. In the current measurement, these weak background contributions are ab-
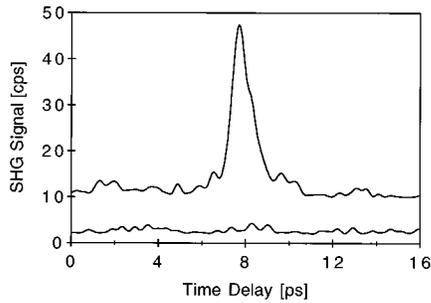
FIG. 5. Temporal waveform obtained using second harmonic generation. The upper curve corresponds to the generation of an electrical transient by the application of a 10 V bias across the pump photoconductor gap. The lower curve is a reference scan obtained in the absence of an applied bias. Both waveforms are offset from the origin for clarity.

sent, as demonstrated by the bias dependence minimum in Fig. 4. The lack of a background SH response is due to the amorphization of the silicon during ion implantation[16] and the well-established selection rule that an isotropic sample will not produce an SH signal for s-polarized excitation and s-polarized detection. We note that similar results may be achieved with appropriately oriented crystalline silicon.[12]

We measured the transient electric field by placing a bias on the gap of the pump photoconductor (see Fig. 1) and gating the corresponding photoconductive gap with an average optical power of 70 mW. The probe beam had an average optical power of 100 mW. The time-resolved SH intensity $I^{(2\omega)}_{x,x}$ for pump finger biases of 10 and 0 V is shown in Fig. 5. Using the data from Fig. 4, we estimate that the peak in the upper curve of Fig. 5 corresponds to a maximum voltage of approximately 500 mW on the center line. The width of the temporal SH waveform was approximately 1 ps FWHM. For an idealized measurement with an instantaneous nonlinear optical response, the temporal waveform derived from the SH intensity measurement may be related to the time delay τ by

$$I^{(2\omega)}(\tau) \propto \int_{-\infty}^{\infty} [I^{(\omega)}(t)E_{tr}(t-\tau)]^2 dt. \qquad (3)$$

The intrinsic response time for such a measurement is limited by the spread in the arrival time of the probe beam throughout the probed volume and the properties of the nonlinearity. Given the short escape depth (125 nm) for the SH signal and the expected electronic nature of the nonlinearity, an intrinsic response time of <10 fs may be expected. We compare the results of the SH measurement with the electronic cross-correlation data. From the inferred single-gap pulsewidth of 1.1 ps FWHM and an optical probe pulsewidth of 150 fs FWHM, we obtain from Eq. (3) a calculated pulsewidth for the SHG measurement of 0.9 ps. This is in reasonable agreement with the experimentally determined value.

In our current experimental arrangement, the photon energy of the probe beam lies above the band gap of silicon. Thus, the probe beam produces both photocarriers and heat, limiting the laser intensity that may be applied (in our measurement, a laser power was chosen for which neither of these effects appeared to be important). A substantial improvement in the signal to noise ratio may, therefore, be expected by using a photon energy for the probe lying below

the band gap of Si. In this case, the technique would remain nonperturbative even for higher probe intensities. Since the observed SH signal will still originate from the surface region of the silicon, the escape depth for the SH radiation (which lies above the band gap) will remain short. Furthermore, significantly tighter focusing of the incident probe beam, coupled with a reduction in the optical pulse duration, will yield a substantial enhancement in the sensitivity.

In conclusion, we have demonstrated the detection of picosecond electrical pulses using optical SHG in silicon. Since the method exploits the nonlinear optical response of silicon itself, it requires no additional probes or crystals and is noninvasive. In this work, a detection sensitivity of 100 mV/$\sqrt{\text{Hz}}$ has been obtained with subpicosecond time resolution for an optoelectronically generated electrical transient propagating on a coplanar transmission line. Further improvements in time resolution and sensitivity may be expected with refinements in the technique.

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