Subpicosecond electrical pulse generation by edge illumination of silicon and indium phosphide photoconductive switches

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Using a femtosecond pulsed laser, ultrafast electrical pulses were optoelectronically generated on silicon and indium phosphide by edge illumination of a coplanar transmission line. Backing up theory with experiment, we demonstrate that this pulse-generation method is material independent, thus providing a powerful tool for broadband characterization of devices made on a wide range of semiconductor substrates. We also demonstrate that edge illumination enables the generation of 550 fs electrical pulses on indium phosphide and 800 fs pulses on silicon—the fastest pulses to date on bulk silicon. © 1995 American Institute of Physics.

The use of subpicosecond electrical pulses is becoming increasingly important as a tool for broadband characterization of ultrafast electronic circuits. Ultrafast electrical pulses have already been exploited to perform broadband frequency domain characterization of circuits1–2 and for test and failure analysis of digital circuits.3 These pulses have frequency components in the terahertz regime and have been used for the characterization of transmission lines for high-speed interconnections on integrated circuits.1 Microwave S parameters have also been measured using ultrafast electrical pulses.2

Several methods for the generation of ultrafast electrical pulses have been developed using pulsed lasers on semiconductors.4–6 Some of these techniques require special materials or geometries that make it difficult to use these methods as an analysis tool, as in Ref. 2. However, edge illumination, first demonstrated by Krökel et al.,3 requires no special designs other than a coplanar transmission line, which is common on many chips today. The subpicosecond electrical pulse is created by electrically biasing the transmission line and illuminating only a small area of semiconductor between the transmission lines with a laser pulse. This phenomenon has been well studied on GaAs substrates.6–10 The experiments of Alexandrou et al.9 thoroughly characterized the mechanism of edge illumination on GaAs and provided motivation for further study by strongly supporting the material-independent theory by Sano and Shibata.11 To further reinforce this theory, the effect of edge illumination must be shown on semiconductors other than GaAs.

Sano and Shibata’s theory begins with the premise that a pulsed laser photoexcites carriers that screen the electric field between the transmission lines; thus, the electric field profile quickly changes. Maxwell’s equations assert that a change in the electric field produces a displacement current. This is the subpicosecond electrical pulse that propagates on the transmission line. The propagating pulse has a width determined by the speed with which the electric field redistributes itself between the transmission line electrodes. Following this, the photoexcited carriers will recombine or be swept out, causing the electric field to relax to its original profile. This is a much slower relaxation process and causes a localized electric field that does not propagate. When measured close to the excitation point, this localized step is seen as a shoulder following the initial pulse. The shoulder can be either positive or negative depending on where the measurement is taken.3 Both the propagating ultrafast pulse and the localized effect, predicted by Sano and Shibata, were observed experimentally in GaAs.9

In this letter, we report experimental studies of edge illumination of coplanar transmission lines on Si and InP. Our experiments add further evidence that the ultrafast electrical pulses produced by edge illumination are the result of an electromagnetic field disturbance. By applying the method of edge illumination to Si, we demonstrate a mechanism for generating the fastest electrical pulses on Si to date.

A Ti:sapphire laser (with ~140 fs pulses) was used at fundamental (720 and 800 nm) and frequency-doubled (400 nm) wavelengths in conjunction with our electro-optic sampling system.12 The measurement is performed by focusing both the excitation and sampling beams through the same microscope objective onto a LiTaO3 finger probe. The sampling beam is guided in total internal reflection mode, while the excitation beam is sent straight through the crystal.6 Thus, the sampling is performed very near where the pulse is generated in order to reduce pulse dispersion on the transmission line. A dc bias is applied to the transmission line. The optimal excitation point for generating the largest signal, as has been previously determined,9 is at the metal semiconductor interface, as shown in Fig. 1. The signal is then sampled ~100 µm from the excitation point. To show the effects of the local fields, we sampled the electric field at three points across the gap: the anode, cathode, and near the center of the gap. The transmission lines are the 20 µm coplanar strip and Ti/Au or Cr/Au transmission lines with a 15 µm gap fabricated on both unintentionally doped Si (p < 1015) and Fe:InP.

Exciting InP at the cathode with 720 nm (red) light generates the subpicosecond pulses with full width at half maximum (FWHM) of 550 fs, as shown in Fig. 2. Of particular interest is the difference in the shoulders following the pulses. At our sampling point, ~100 µm from the excitation,
we could still observe the effects of the local field by examining these shoulders. Sampling the electric field on the same side as the excitation (curve A) results in the observation of a positive shoulder due to the electric field increasing from its excited state, near zero, to its original profile. Testing on the opposite side (curve C) we observe a negative shoulder caused by the decreasing electric field following the excitation. Finally, by sampling near the center (curve B), the effect of the local field is balanced, and only the propagating pulse is observed. The 720 nm red light on Si produces the pulses shown in Fig. 3. To achieve the largest pulse amplitude, these pulses were produced by excitation near the anode, as in GaAs. These pulses look very different from those produced in InP. Measured within 100 μm from the excitation point, subpicosecond pulses would not have been dispersed this much. However, we can still see the process of a slowly recovering electric field pattern from the shoulders. Because Si has a large penetration depth at 720 nm, we decided to explore the effect of a much smaller penetration depth. As can be seen in Fig. 4, we achieved a remarkable improvement in pulse quality by using 400 nm (blue) excitation. The penetration into Si for blue light is more than an order of magnitude less than for red light. These pulses with ~1 ps FWHM are similar in shape and duration to those of InP excited with red light, and also to those previously obtained on GaAs. Once again we observe the effects of the local electric field: positive shoulder on the excitation side (curve A), negative shoulder on the opposite side (curve C), and no shoulder in the gap at the edge of the excitation pulse (curve B). In order to observe just the propagating pulse, we probed >500 μm from the excitation point in Si and measured an electrical pulse of <2 ps FWHM.

The above results indicate that signal dispersion may have contributed to the broadening of the pulse widths, even on the 100 μm distance scale. In one run, we were able to bring the sample spot <50 μm from the excitation spot and obtained an 800 fs pulse, shown in Fig. 5 (measured on a Cr/Au metallized line). This represents the fastest electrical pulse ever generated on bulk silicon with optoelectronic excitation.

Our results directly support the Sano and Shibata theory. The local field in the vicinity of the excitation is observed,
and only the subpicosecond pulse propagates down the transmission line. We believe our success in generating a pulse on Si is due to our choice of excitation wavelength. The only other successful ultrafast pulse generation on Si, with light having a large penetration depth, was performed on a silicon-on-sapphire (SOS) substrate. The Si layer used in the SOS substrate is much less than the penetration depth at the excitation wavelength; thus, it was possible for Krökel and co-workers\textsuperscript{5} to generate a picosecond pulse. With a shallow absorption length, only the electric field profile near the surface is disturbed causing a surface redistribution of the electric field. This weakens the displacement current from the surface field and thus smears the pulse shape.

Sano and Shibata’s theory is based on transmission lines making an ohmic contact with the substrate and producing a symmetrical electric field distribution. Due to surface states, Schottky contacts and trap levels, the electric field can be much greater at one electrode. This is predicted by Lampert\textsuperscript{13} and experimentally verified by Alexandrou \textit{et al.}\textsuperscript{8,9} In our experiments, both Si and InP were capable of producing propagating electrical pulses when excited at either the anode or the cathode. Optimal pulses were achieved in Si when excited at the anode, as in GaAs\textsuperscript{8,9} while InP exhibited optimal pulses when illuminated at the cathode. The Cr/Au and Ti/Au metallized lines on Si also produced a somewhat different location dependence of the pulse height. These results suggest that a material-dependent combination of surface states, Schottky contacts, and trap levels determine the initial field distribution, and hence a location-dependent pulse distribution across the photoconductive gap.

The band structure in Si is totally different from that of InP and GaAs. Thus, our results show that the mechanism behind edge illumination is not material dependent. Therefore, it appears unlikely that electrical pulses arising from edge illumination is a result of intervalley scattering, as was suggested for GaAs.\textsuperscript{6}

The applicability of this method to a variety of materials (Si, GaAs, and InP) makes edge illumination a convenient technique for ultrafast pulse generation in semiconductors. Another useful feature of edge illumination is that it requires no extra processing; it can be performed with the existing transmission lines on integrated circuits. By utilizing edge illumination, broadband frequency domain characterization of devices fabricated on Si and InP can be as easily performed as those on GaAs. When combined with an electro-optic sampling system, edge illumination is a simple and powerful tool for \textit{in situ} characterization of circuits.

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\textsuperscript{13}M. A. Lampert, Phys. Rev. \textbf{103}, 1648 (1956).