Subpicosecond electrical pulse generation using photoconductive switches with long carrier lifetimes

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Using a new mechanism of electrical pulse generation, we have generated 350 fs (full width at half maximum) electrical pulses on a coplanar transmission line, fabricated on an unimplanted silicon-on-sapphire substrate.

A powerful method of generating picosecond and subpicosecond electrical pulses is based on driving photoconductive switches with ultrashort laser pulses.[1] Recent work has adapted this approach to the so-called "sliding contact" method of pulse generation.[2–4] Here, a charged transmission line fabricated on a photoconductive substrate is shorted via the photocarriers generated by an ultrashort laser pulse focused between the lines. Due to the exceptionally good coupling of the generated pulse to the propagating mode of the line, the response time is very fast and is predicted to follow the transient conductivity of the photoconductive switch.[4] Usually the photoconductive substrate is a silicon-on-sapphire (SOS) wafer, which has been heavily ion implanted to ensure a short carrier lifetime.[5] For this case, the generated electrical pulse has a rapid rise followed by an exponential decay determined by the carrier lifetime of approximately 600 fs. For an unimplanted wafer a step-function pulse is generated with an initial rapid rise time followed by a long pulse tail whose duration is given by the carrier lifetime of approximately 100 ps. The electrical pulse generated on the transmission line can be measured with either a probing photoconductive switch[1,3,4] or by using electro-optic techniques.[2,6]

In this letter we report observations of a new mechanism to generate subpicosecond electrical pulses whose duration is not determined by the carrier lifetime. The key to this approach is the asymmetric irradiation of a charged coplanar transmission line fabricated on an unimplanted SOS wafer. Using this method we have generated and measured electrical pulses as short as 350 fs.

The schematic diagram of the experimental arrangement is illustrated in Fig. 1. The 21-mm-long transmission line had a design impedance of 100 Ω and consisted of two parallel 5-μm-wide, 1-μm-thick aluminum lines separated from each other by 10 μm. The measured dc resistance of a single 5 μm line was 9 Ω/mm. The LiTaO$_3$ crystal had dimensions of 2 mm $\times$ 3 mm $\times$ 0.1 mm and was contacted to the silicon side of the SOS substrate with the z axis in the 2 mm $\times$ 3 mm plane of the crystal and perpendicular to the transmission line. We used the same 20× microscope objective lens to focus both the 4 mW exciting and 4 mW sampling beams on the 0.5-μm-thick silicon layer. The 625 nm, 70 fs laser pulses were from a compensated, colliding-pulse, mode-locked dye laser with a 100 MHz pulse repetition rate. The beams entered the wafer from the polished sapphire side and exited at the silicon side, where the focused beam size was approximately 4 μm in diameter. The generated electrical pulse was measured by monitoring the change in polarization of the sampling beam due to the presence of the pulse, using an optical arrangement similar to that previously described.[6] As shown in the figure, in order for our new pulse generation mechanism to operate, the laser beam must be focused to a spot smaller than the separation between the two lines of the coplanar transmission line. For optimum performance the small laser spot should partially illuminate the back side of the positively charged line.

Our measurement of the generated pulse under the above conditions is illustrated in Fig. 2(a). This measurement was taken 100 μm away from the excitation site. Here the rise time is 260 fs with a full width at half maximum (FWHM) pulsewidth of only 350 fs. This result showing our shortest electrical pulse was obtained by optimizing the position of the excitation beam with respect to the positive line. From our calibration of the strength of the electro-optic effect versus voltage on the transmission line, we determined the amplitude of the generated pulse to be approximately 180 mV. This value is to be compared with the bias voltage of + 10.5 V. Characteristically, we always observed a strong short pulse followed by a much weaker step function. Although the signal strength is proportional to the bias voltage across the line, the general features of the observed pulse are independent of bias voltage from approximately + 1.5 to + 20 V. However, when the voltage polarity is changed, the initial short pulse changes sign and is reduced in amplitude by 10 times, as shown in Fig. 2(b). The small rapid oscillations are an optical interference effect at the detector and are independent of the electrical pulse on the line. When the focal spot size is increased to completely fill the space between the two lines, the short pulse disappears and the expected step function for unimplanted material is obtained as shown in Fig. 2(c). The rise time of 690 fs is almost three times that of Fig. 2(a), and the pulse amplitude has more than doubled. This pulse decays with the carrier lifetime of

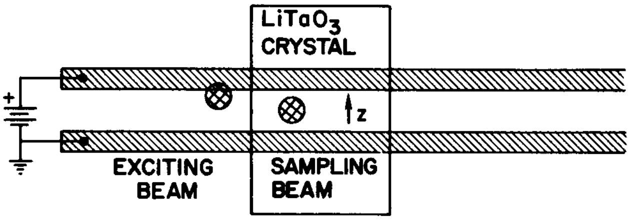

FIG. 1. Schematic diagram of the experiment. The coplanar transmission line consists of two 5-μm-wide by 1-μm-thick aluminum lines separated from each other by 10 μm, fabricated on a silicon-on-sapphire substrate.

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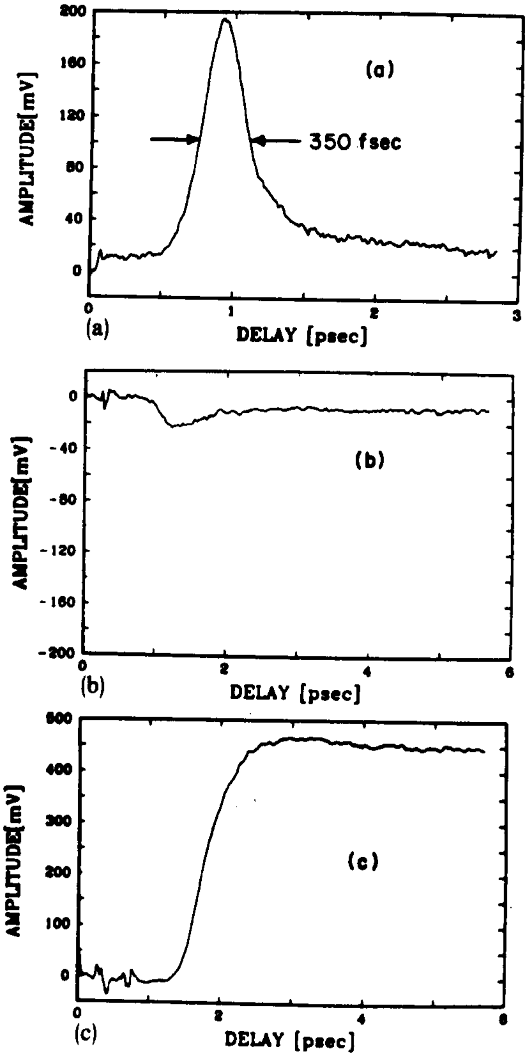

FIG. 2. Measured electrical pulse with 10.5 V across the lines. (a) Small diameter exciting beam in contact with the positive line. (b) Polarity reversed; small diameter exciting beam in contact with the negative line. (c) Diameter of the exciting beam increased to completely fill the separation between the two lines.

approximately 100 ps. In contrast to the observations of Figs. 2(a) and 2(b), for the step function changing the voltage polarity reduces the amplitude by approximately 30% together with changing the polarity of the observed pulse. We have repeated these measurements using ion-implanted photoconductive switches (gaps) for the detection. The same effects were observed, but with somewhat lower time resolution due to the longer response time of the gap. We have also observed changes in shape due to propagation on the line. In this regard it is important to note that, because of the asymmetric excitation for Fig. 2(a), the generated pulse does not match the propagating (differential) mode of the transmission line. Rather, the pulse is a linear superposition of both the common mode and the differential mode. This superposition causes the pulse to broaden more rapidly as it propagates down the line.

We are currently working to understand the physics of this new pulse generation mechanism. An intuitively appealing model involves the instantaneous formation of a very conductive region, defined by the laser spot, which becomes an equipotential with the positive line. This change in conductor geometry gives rise to a capacitance increase δC to produce an electrical pulse comparable to that which would be produced by the instantaneous addition of a charge $\delta Q = V\delta C$ to the line. Such a simple picture does not by itself explain the asymmetry in the polarity of the bias voltage. Possible explanations of this asymmetry require a more detailed examination of the metal-silicon-metal transmission line structure which, in the simplest case, consists of two ideal back-to-back Schottky barrier diodes. The diode at the one line is reverse biased while the diode at the other line is forward biased. For this case almost all of the dc voltage applied to the transmission line is dropped across the depletion region of the reverse biased diode. Thus, at one line our intuitive model should apply, while at the other line little if any effect is expected, since that entire region is already nearly an equipotential. Another possible explanation is that there are a large number of mobile surface ions (Na for example) on the unpassivated silicon surface which move to the vicinity of the negative electrode when a voltage is applied, leaving most of the potential drop near the positive electrode. Again the mechanism of our intuitive model would imply a much larger effect at the positive electrode. As evidence of the asymmetry of the electric field in the silicon between the lines, we have detected a 5% asymmetry for the dc electric field above the lines via the sampling beam passing through the electro-optic crystal. Additional experiments are in progress to help develop a more detailed picture of the pulse generation mechanism.

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