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Capacitance Free Generation and Detection of Subpicosecond Electrical Pulses on Coplanar Transmission Lines

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Abstract—**Based on a reanalysis of previous work and new experimental measurements, we conclude that the parasitic capacitance at the generation site is negligible for sliding contact excitation of small dimension coplanar transmission lines.**

THE generation of short electrical pulses via optical methods has for some time been performed by driving Auston switches (photoconductive gaps) with short laser pulses [1]. The generated electrical pulse is determined by the laser pulse, the carrier lifetime in the semiconductor, the capacitance of the switch, and the characteristic impedance of the electrical transmission line. The same techniques can also measure the resulting electrical pulses by sampling methods. Recent work utilizing photoconductive gaps has generated and measured subpicosecond electrical pulses [2]. This large reduction in the generated pulsewidth demonstrates the ultrafast capability of the Auston switches and calls for an understanding of the fundamental limits of their generation and detection processes.

Stimulated by recent direct measurements [3], [4] of the carrier lifetime in ion-implanted silicon-on-sapphire (SOS), we have reanalyzed the results of [2]. Based on this analysis, we have come to the conclusion that, for the so-called "sliding-contact" method of excitation [2], [5], to first order the capacitance of the photoconductive switch at the generation site is zero. This conclusion is further supported by an experimental measurement of an ultrashort electrical pulse using the double sliding-contact method of generation and detection [6] where, to first order, the capacitances at both the generation and detection sites are zero. This measurement is in excellent agreement with a theoretical analysis which assumes that the duration of the generated electrical pulse was limited only by the laser pulsewidth and the carrier lifetime. This conclusion removes one of the most severe limitations, associated with the circuit parameters, on the generation of ultrashort electrical pulses by photoconductive switches. The remaining limitations are the carrier lifetime, where recent progress has been made [4], and the laser pulsewidth itself.

We will briefly review the initial experiment and its analysis to provide the background for this recent advance. The geometry of the experimental arrangement [2] is illustrated in Fig. 1(a). The 20 mm long transmission line had a design impedance of 100 Ω and consisted of three parallel 5 μm aluminum lines separated from each other by 10 μm. The dc resistance of a single 5 μm line was 200 Ω. The transmission line, composed of a 0.5 μm thick Al film, was fabricated on an undoped silicon-on-sapphire (SOS) wafer, which was heavily implanted with 0+ ions to ensure the required short carrier lifetime.

The laser source is a compensated, colliding-pulse, passively mode-locked dye laser producing 80 fs pulses at a 100 MHz repetition rate. The measurements were made with the standard excite and probe arrangement for the beams of optical pulses. The time delay between the exciting and sampling beams was mechanically scanned by moving an air-spaced retroreflector with a computer-controlled stepping motor synchronized with a multichannel analyzer. The measured subpicosecond electrical pulse with an excellent signal-to-noise ratio is shown in Fig. 1(b). For this result, the spatial separation between the exciting and sampling beams was approximately 50 μm, while the laser spot diameters were 10 μm.

Our initial analysis [2] of this pulse followed Auston's theory [1], which is extremely general and applies to practically any transmission line configuration. The theory only assumes (for both the generation and detection sites) a conductance, given by the convolution of the laser pulse and the carrier lifetime, charging a capacitance. Each capacitance C discharges with time constant ZC where Z is approximately the transmission line impedence. The numerical fit shown as the solid line in Fig. 1(b) was obtained with the following parameters. The conductances of both the sliding contact generation site and the sampling gap site $g_1(t)$ and $g_2(t)$, respectively, were assumed to be given by the convolution of the laser pulse (allowing for its spatial extent) with an exponential

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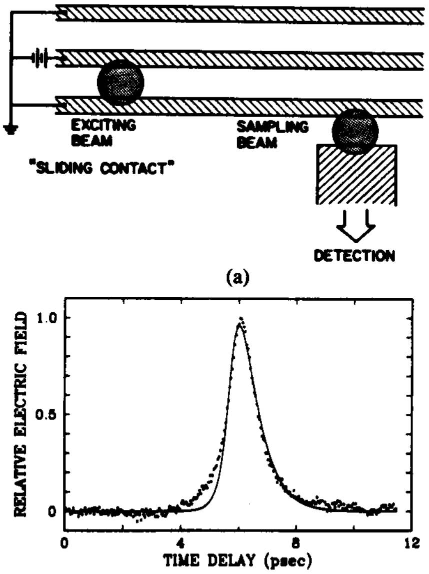

(a)

(b)

Fig. 1. Experimental geometry of [2]. (b) Measured electrical pulse (dots) compared to theory of [2] with t_c = 250 fs, C_{sc} = 1 fF, and C_s = 4 fF.

response function describing the carrier lifetime t_c. For this initial analysis, t_c was assumed to be 250 fs. An intuitive argument presented in [2] led to the values of the capacitance at the generation site C_{sc} = 1 fF and at the sampling site to be C_s = 4 fF. As can be seen, the fit is reasonably good, with the exception that the leading edge of the calculated pulse rises much faster than the experiment. Later analysis indicated that the shortness of the assumed carrier lifetime (compared to the measured pulse) was responsible for this deviation. A recent direct measurement of the carrier lifetime for heavily implanted SOS obtained the value of t_c = 600 fs [3], and thereby confirmed this situation. This measurement forced the following reanalysis of the generation process for the electrical pulse.

We will now discuss some general aspects of transmission line theory in the quasi-static limit (QSL) for which the wavelengths involved are large compared to the transverse dimensions of the line. For this case, the number of transverse electromagnetic (TEM) modes is one less than the number of metal lines making up the transmission line. Consequently, a two-line transmission line has a single propagating TEM mode. In the QSL, the electric field distribution of this mode is the same as for the static case when the lines are equally and oppositely charged. Any pulse propagating on this line can be described mathematically as a Fourier sum of single frequency components, all with this same TEM modal distribution. Likewise, a transient "purely electric" pulse of a limited spatial extent can be considered to be the sum of two counterpropagating pulses with the same spatial extent. For this "stationary" electrical pulse, the zero H field comes from the superposition of the two counterpropagating pulses where the E fields add, but the H fields subtract. The key point in the argument to follow is that for sliding-contact excitation, the resulting electrical transient is equivalent to the superposition of two counterpropagating electrical pulses due to the zero H field and to the excellent match of the E field lines to the propagating TEM mode. This essentially perfect coupling eliminates the parasitic capacitance (and inductance) at the excitation site.

Consideration of the sliding-contact excitation site shows that, to first order, charge is simply transferred from one line to the other, creating a symmetrical field distribution with respect to the two lines. During the excitation process, a current flow is induced between the lines. Localized charge accumulations of opposite sign build up on the segments of the two metal lines under the laser excitation spot, creating a dipolar field distribution similar to that illustrated in Fig. 2(a). The response time of this field pattern is approximately the time required for electromagnetic radiation to cross the separation between the two lines. For the simplified quasi-static picture to apply, this time should be short compared to either the laser pulse duration or the carrier lifetime, whichever is longer. This is simply a restatement that the wavelengths involved should be large compared to the transverse dimensions of the line. Because the electric field lines of the TEM mode have the same pattern as the dc field lines [illustrated in Fig. 2(a)] when the lines are equally and oppositely charged [7], the sliding-contact excitation is well matched to the TEM mode. The major part of generated field pattern is the same as this TEM mode which is perfectly coupled to the line.

A most important feature of a coplanar transmission line (of negligible thickness) on an infinite dielectric half-space is that for a constant voltage between the two conducting lines, the electric field lines are the same as for the lines immersed in free space [8]. This result is due to the geometric symmetry with respect to the dielectric boundary and is a consequence of the fact that no electric field lines cross this boundary. The effect of the dielectric (with dielectric constant ϵ) is to increase the surface charge density on the conductors in contact with the dielectric to $\epsilon\sigma_0$ where σ_0 is the surface charge density in free space. However, because there is a polarization surface charge density of $(\epsilon - 1)\sigma_0$ of the opposite sign, the net surface charge remains σ_0, keeping the electric field the same. Consequently, the main effect of the dielectric is to increase the distributed line capacitance. This increase will now be evaluated following the procedure of [8]. Consider the capacitance per unit length of the line to be C_0 in free space. In the dielectric medium, the surface charge density is $\epsilon\sigma_0$, but for the side of the line in free space, the surface charge density remains σ_0. Therefore, for the same voltage between the lines, the charge has increased by $(1 + \epsilon)/2$, and the corresponding capacitance has increased to $C = (1 + \epsilon)C_0/2$. Because we assume the dielectric medium has a magnetic permeability equal to unity, the inductance L_0 per unit length does not change in the presence of the dielectric.

The predicted group velocity can now be evaluated following the logic of [8]. For the transmission line in free

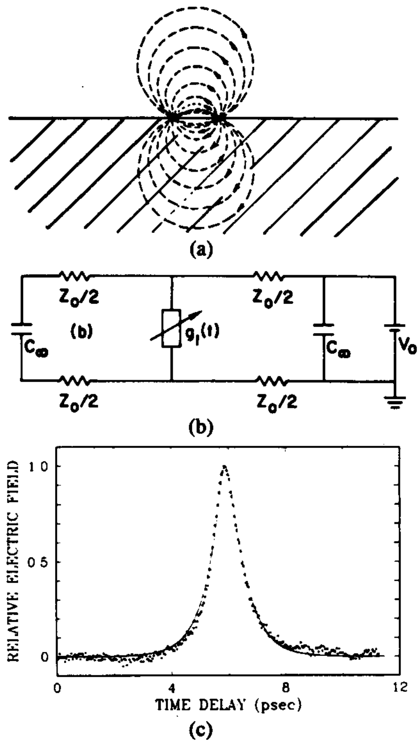

Fig. 2. (a) Electrical field lines for the propagating TEM mode (differential mode) of a two-line transmission line in a uniform dielectric and on the surface of a uniform dielectric. (b) Equivalent circuit for sliding-contact excitation of a two-line transmission line. (c) Measured electrical pulse (dots) of [2] compared to theory with t_c = 600 fs, $C_{sc} = 0$, and C_s = 1 fF.

space, the group velocity v_g is given by $v_g = (1/(L_0C_0))^{1/2} = c$ [9], [10]. In the presence of the dielectric, the capacitance has increased to $(1 + \epsilon)C_0/2$, while the inductance remained the same. This situation gives the result $v_g = c(2/(\epsilon + 1))^{1/2}$. The low-frequency dielectric constants of sapphire are 9.4 for the ordinary ray and 11.6 for the extraordinary ray [11]. These values give the corresponding group velocities of $c/2.28$ and $c/2.51$, which bracket our measured value [2] of $c/2.45$ obtained on sapphire of unknown orientation. This good agreement confirms the validity of the quasi-static approximation and shows that the TEM mode remains a good approximation for this split dielectric case, even though it is no longer an exact solution. Consequently, all of the above arguments also apply to the split dielectric case, i.e., sliding-contact excitation produces a field distribution which matches the propagating mode of the line, and thereby the parasitic capacitance at the generation site is negligible.

An equivalent circuit illustrating this situation is shown in Fig. 2(b) where the photoconductance $g_1(t)$ created by the laser excitation is connected directly across the characteristic (resistive) impedance Z_0 in either direction. The infinite capacitances simply illustrate that the line extends without end in both directions. Because this circuit has no capacitance at the generation site, the voltage pulses launched in both directions down the line are given by $V(t) = V_0Z_0/(Z_0 + 1/g_1(t))$. For our case where $V(t) \ll V_0$, this result simplifies to $V(t) = V_0Z_0g_1(t)$. Consequently, the generated electrical pulse has the same time dependence as the conductance $g_1(t)$.

We again numerically analyzed the measured electrical pulse of Fig. 1(b), but with the following parameters. The conductances $g_1(t)$ and $g_2(t)$ were obtained as before, except now the carrier lifetime is known to be 600 fs. The capacitance at the generation site was set equal to zero, $C_{sc} = 0$. Thus, the capacitance at the sampling site was the only adjustable parameter to be determined by numerically fitting to the measured pulse. With the optimized value C_s = 1 fF, we obtained the excellent agreement with theory shown as the solid line in Fig. 2(c). For this situation, the actual generated electrical pulse was calculated and is shown in Fig. 3 to have a pulsewidth of only 0.52 ps. The sharp rising edge is due to the short laser pulse excitation, while the slower falling edge of the pulse is due to the 600 fs carrier lifetime. This pulse is directly proportional to $g_1(t)$ in accordance with the analysis of the equivalent circuit of Fig. 2(b).

The good agreement between theory and experiment in Fig. 2(c) gave us confidence in our new understanding of the pulse generation process and suggested as a further confirmation the experiment illustrated in Fig. 4(a). This more symmetrical arrangement is called the double sliding-contact and has no observable capacitance [6]. It is to be noted that we used a two-line transmission line, so that the above arguments about matching to the propagating TEM mode are more precise. The electrical pulse is generated as before, but here the sampling measurement is also made by shorting the transmission line with the sampling laser pulse. For this case, the two laser beams are mechanically chopped at incommensurate frequencies and the signal is measured as a modulation of the photocurrent on the transmission line at the sum of the two chopping frequencies. Because to first order this arrangement has no capacitance at both the generation and sampling sites, the measured electrical pulse had a pulsewidth of only 0.85 ps compared to the previous measurement of 1.1 ps using a sampling gap. This measurement was made on a smaller geometry coplanar line with line dimensions of 1.2 μm separated by 2.4 μm. The design impedance was 100 Ω and the bias was 1.5 V. In order to compare to theory, the conductances $g_1(t)$ and $g_2((t)$ were obtained as before with the carrier lifetime of 600 fs, but now the capacitances at both the generation and sampling sites were set to zero. The resulting fit to the data is shown as the solid line in Fig. 4(b). This theoretical prediction is equivalent to the autocorrelation of the electrical pulse shown in Fig. 3. The agreement between theory and experiment showing the sharpness of the peak of the pulse is good. This extremely sharp peak is due to the sharp leading edge of the generated electrical pulse in Fig. 3.

However, the data in Fig. 4(b) definitely show a faster time dependence than the calculations which only assume an excitation pulse of 130 fs (the square root of the sum of the squares of the laser pulsewidth plus the transit time due to the 10 μm diameter spot size) and the 600 fs carrier lifetime.

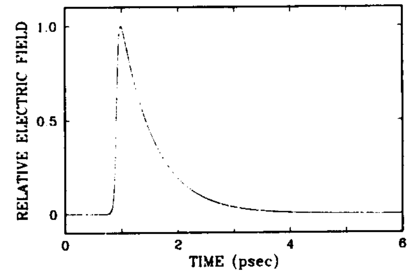

Fig. 3. Generated electrical pulse.

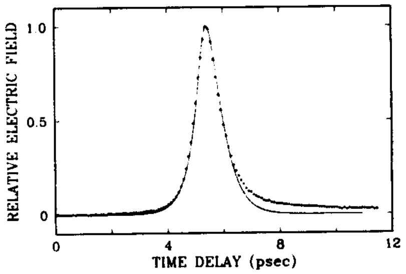

Fig. 5. Measured electrical pulse (dots) compared to theory with t_c = 400 fs, C_{sc} = 0 fF, and C_s = 2.5 fF.

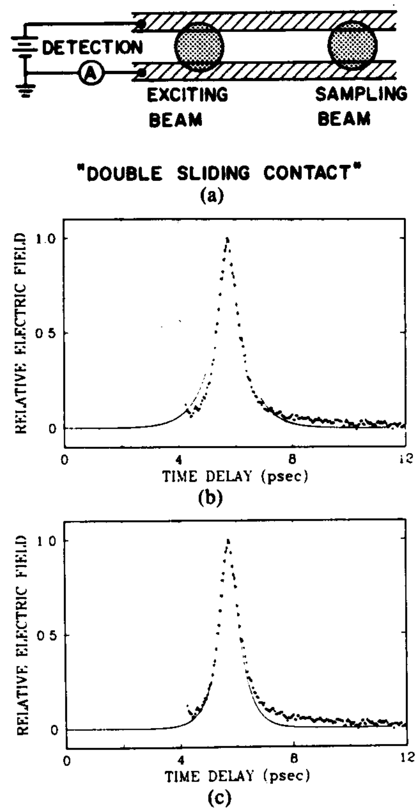

Fig. 4. (a) Experimental geometry for double sliding contact. (b) Measured electrical pulse (dots) compared to theory with t_c = 600 fs, C_{sc} = 0 fF, and C_s = 0 fF. (c) Measured electrical pulse (dots) compared to theory with t_c = 400 fs, C_{sc} = 0 fF, and C_s = 0 fF.

Because the 600 fs data were obtained by reflectivity measurements [3], [4], it is natural to assume that they were a surface-sensitive measure of the carrier lifetime. However, a recent analysis [12] has shown that this was not the case, and that for a 0.5 μm thick layer of silicon on a sapphire substrate, the main component on the signal obtained with 620 nm light was due to the induced change in the optical length of the silicon, due to the change in the index of refraction. This thin-film, interference-enhanced signal can be as much as 20 times larger than the comparable change in reflectivity from the single surface of a thick silicon wafer. Consequently, the measurements of the carrier lifetime of [3], [4] are representative of the entire silicon film and not just the surface layer. As such, it is possible that the relevant carrier lifetime for optoelectronic pulse generation and measurement could be shorter due to their surface sensitivity and the presence of additional traps at the surface.

This conjecture was tested by reanalyzing the data of Fig. 4, using a carrier lifetime of 400 fs, which appears to give a significantly better fit as shown in Fig. 4(c). The capacitances were, of course, kept equal to zero.

In order to provide more information on this point, we compare a calculation to some recently measured high signal-to-noise data shown in Fig. 5. This pulse was generated by sliding-contact excitation of a two-line transmission line consisting of 5 μm lines separated by 10 μm, and was detected with a side gap similar to that shown in Fig. 1. As previously mentioned, the zero capacitance argument is more precise for this two-line case. The theoretical comparison shown as the solid line in the figure fits the rising edge and the main pulse itself exceedingly well. The deviation on the falling edge is thought to be due to resistive line effects. Again, this was fit with a 130 fs excitation pulse, a 400 fs carrier lifetime, zero capacitance at the generation site, and for this gap, a 2.6 fF capacitance. These parameters correspond to a generated electrical pulse of only 0.45 ps with a shape similar to that shown in Fig. 3.

In summary, by reanalyzing the first experiment to generate subpicosecond pulses using photoconductive switches, we have shown that to first order, the sliding-contact generation site has no capacitance. This conclusion is further supported by a double sliding-contact experiment where, to first order, neither the generation nor the detection site has any capacitance. This result removes the parasitic capacitance of the electrical circuit as one of the major difficulties to short electrical pulse generation using photoconductive switches.

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REFERENCES

[1] D. H. Auston, "Impulse response of photoconductors in transmission lines," *IEEE J. Quantum Electron.*, vol. QE-19, pp. 639-648, 1983.
[2] M. B. Ketchen, D. Grischkowsky, T. C. Chen, C.-C. Chi, I. N. Duling, III, N. J. Halas, J.-M. Halbout, J. A. Kash, and G. P. Li, "Generation of subpicosecond electrical pulses on coplanar transmission lines," *Appl. Phys. Lett.*, vol. 48, pp. 751-753, 1986.
[3] F. E. Doany, D. Grischkowsky, and C.-C. Chi, "Carrier lifetime

versus ion-implantation dose in silicon on sapphire," *Appl. Phys. Lett.*, vol. 50, pp. 460–462, 1987.

[4] ——, "Photoconductive generation of sub-picosecond electrical pulses and their measurement applications," in *Proc. 2nd Topical Meet. Picosecond Electron. Optoelectron.*, Incline Village, NV, Jan. 1987.

[5] D. R. Dykaar, T. Y. Hsiang, and G. A. Mourou, "Development of a picosecond cryo-sampler using electro-optic techniques," in *Picosecond Electron. Optoelectron., Proc. Topical Meet.*, Lake Tahoe, NV, Mar. 1985, G. A. Mourou, D. M. Bloom, and C.-H. Lee, Eds. Berlin, Heidelberg: Springer-Verlag, 1985, pp. 249–252.

[6] P. G. May, G. P. Li, J.-M. Halbout, M. B. Ketchen, C.-C. Chi, M. Scheuermann, I. N. Duling, III, D. Grischkowsky, and M. Smyth, "Picosecond electrical pulses in microelectronics," in *Ultrafast Phenomena V*, G. R. Fleming and A. E. Siegman, Eds. New York: Springer-Verlag, 1986, pp. 120–122.

[7] R. E. Collin, *Field Theory of Guided Waves*. New York: McGraw-Hill, 1960.

[8] C. J. Chen and D. Grischkowsky, "Cerenkov radiation from coplanar transmission lines," to be published.

[9] R. E. Matick, *Transmission Lines for Digital and Communication Networks*. New York: McGraw-Hill, 1969.

[10] This is the usual expression for the phase velocity, but for a dispersion-free dielectric, it also describes the group velocity.

[11] E. E. Russell and E. E. Bell, "Optical constants of sapphire in the far infrared," *J. Opt. Soc. Amer.*, vol. 57, pp. 543–544, 1967.

[12] F. E. Doany and D. Grischkowsky, "Measurement of ultrafast 'hot' carrier relaxation in silicon by thin-film-enhanced, time-resolved reflectivity," to be published.

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