Guided Surface Waves in Photoconductive Excitation

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Abstract— **We have used electrooptic sampling to measure photoconductively generated signals on coplanar striplines. We observe a new feature in the measured signal that we attribute to photoconductively-excited surface waves. Measurements at positions laterally displaced from the center of the transmission line show that when the substrate is thin, this signal is confined to the region of the electrodes. We also show that this feature, which can interfere with accurate device characterization, can be eliminated by delaying it out of the time window of interest.**

I. Introduction

IT IS WELL KNOWN that a photoconductive switch is capable of generating electromagnetic radiation with terahertz bandwidth [1]. The radiation coupled into the transmission line has been used for signal generation in high-speed device measurement techniques such as electrooptic [2] and photoconductive sampling [3]. Alternately, photoconductively-generated freely propagating radiation can be collected by a lens on the back side of the substrate and used for free-space transmission measurements [4]. While these two types of experiments are often considered separately, one should expect that both types of radiation will normally be generated, and therefore a transmission line signal will be accompanied by one or several surface-wave modes.

Paulter has described a feature observed by photoconductive sampling that was attributed to a reflection from the back surface of the substrate [5]; Baynes has made similar observations in photoconductive excitation of coplanar waveguides [6]. The presence of surface-wave signals in the characterization of electronic devices can complicate the interpretation of such measurements; from this point of view their presence is problematic. In this letter, we describe observations of a photoconductively generated signal on a coplanar transmission line that we attribute to excitation of surface-wave modes. We study the effect of substrate thickness on the surface-wave properties, and discuss their physical origin.

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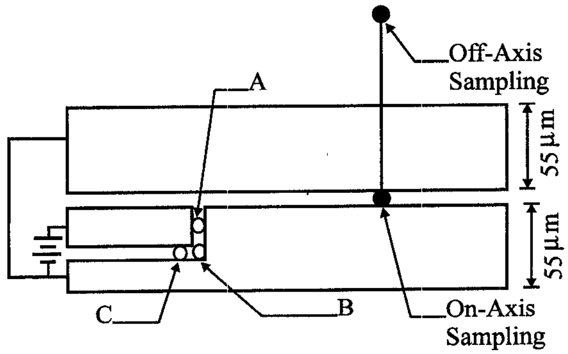

Fig. 1. Layout of coplanar stripline with a photoconductive generator (not to scale). All gaps are 5 μm, and locations A, B, and C are the excitation positions referred to in the text.

II. Experiment

The coplanar stripline (CPS) shown in Fig. 1 is photolithographically patterned on 650-μm-thick semi-insulating GaAs substrates; evaporation of 10-nm/200-nm-thick Ti/Au is followed by liftoff. The sample was mounted on thick non-metallized fiberglass printed circuit board material for characterization. The pattern allows various directions of dipole polarization by signal excitation at locations A, B, and C; dimensions are shown in Fig. 1. Electrooptic measurements are made with 150-fs pulses from a Titanium–Sapphire laser, and an external $LiTaO_3$ electrooptic sampling tip with footprint approximately 220 μm square. The y-cut $LiTaO_3$ crystal is oriented with the optical axis parallel to the substrate surface and perpendicular to the transmission line; this configuration is primarily sensitive to transverse electric fields. We use noncontact probing with an air gap between electrooptic transducer and transmission line of approximately 10 μm for all measurements. In addition to measurements on the axis of the transmission line, we also make measurements with the probe tip laterally displaced from the center; we will refer to these as on- and off-axis, respectively.

III. Results

In Fig. 2(a) the solid line shows the on-axis signal for a 650-μm substrate. The sampling location for this case is approximately 1.67 mm from the photoconductive switch, and excitation is at position A of Fig. 1. As expected with the long-lifetime semi-insulating substrate, the generated signal is step-like. At around 16 ps, however, a new oscillatory feature is seen with a period of approximately 1.5 ps. One might expect this feature to depend upon the direction of charge separation

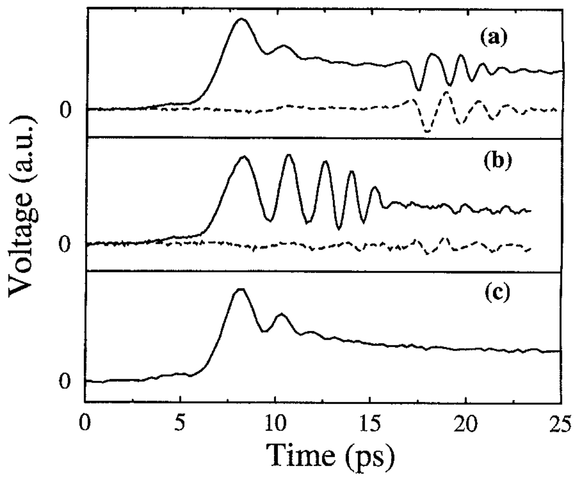

Fig. 2. Measured signals for three substrate thicknesses. (a) On-axis (solid line) and off-axis (dashed line) measurements for a 650-μm-thick sample. (b) On-axis (solid line) and off-axis (dashed line) measurements for the 83-μm-thick sample. (c) On-axis measurements for the 1.3-mm-thick sample.

following photoexcitation. We checked this by excitation at the three locations A, B, and C of Fig. 1. At all three positions we observe similar oscillatory signals, indicating that the charge separation responsible for generation of the feature we see is perpendicular to the metal–semiconductor interface.

We also made measurements off-axis at a distance 350 μm from the center of the transmission lines. At this position, well outside the electrodes, we detect only a small signal from the CPS mode; any observed signal is related to the field of surface-wave modes. In Fig. 2(a), we show the off-axis measurement as a dashed line. The main feature is oscillatory and starts at approximately 16 ps. It is nearly identical in amplitude to the oscillatory feature observed on-axis. Similar waveforms are observed at distances as great as 500 μm away from the transmission line; the amplitude is weakly dependent on lateral displacement.

To study the role of the substrate we prepared a sample with 83-μm thickness by mechanical lapping. In Fig. 2(b), we show the on- and off-axis measurements as the solid and dashed lines, respectively; sampling and excitation conditions are the same as those for Fig. 2(a). To facilitate comparison the three panels of Fig. 2 have been time-shifted to align the leading edges of the on-axis signals. The on-axis signal in Fig. 2(b) has oscillatory features appearing immediately after the initial peak, much earlier than in the case of Fig. 2(a); in the thin sample the relative amplitude of these features is much greater. The off-axis measurement is very different from that seen in Fig. 2(a), with no obvious evidence of an oscillatory feature.

Because these oscillatory features are not obviously related to propagation in the fundamental CPS mode, it is important to be able to eliminate them from measurements of electronic devices. In [5], microwave-absorbing material on the backside of the substrate was used to eliminate the backside reflections. An alternative approach is demonstrated in Fig. 2(c), where the 650-μm sample being tested is placed on another unpatterned substrate of equal thickness. In this case the sampling location was 1.5 mm from the photoconductive switch and located on-axis. Only a step-like signal is seen in the time window shown, and there is no evidence of a reflection from the interface between the two substrates.

IV. Discussion

In the following, we focus our attention on the physical origin of the oscillatory features seen in Fig. 2; it can be seen from this figure that the arrival time relative to the CPS signal is related to substrate thickness; this energy must be propagating deep in the substrate. Baynes has suggested that such signals can be explained as the superposition of a coplanar-transmission-line signal and a bulk wave that is reflected from the backside of the substrate [6]. Using this ray-optics picture, the relative delay between the two signals can be estimated using the quasistatic dielectric constant $(\epsilon_r+1)/2$ for the CPS mode, and ϵ_r for the surface wave. Such an estimate of the delay time is in good agreement with our measured relative delays. While such a ray-optics picture is intuitively appealing, it is inadequate. With a period of 1.5 ps, the wavelength in the substrate is approximately 125 μm; our smallest substrate thickness of 83 μm is therefore comparable to the wavelength, as is the total width of the coplanar stripline (115 μm); a description in terms of modes is required. The modes relevant in the present coplanar stripline are the dominant CPS mode, surface-wave modes of the ungrounded dielectric far from the CPS electrodes, and surface-wave modes under the metallic electrodes [7]; this last type of mode is often called "surface-wave-like."

Two explanations are possible for the origin of the signals we observe; the first relates to leakage from the dominant CPS mode. The interaction of the surface-wave modes with the dominant modes of a coplanar waveguide (CPW) has been described by Tsuji [8]. They showed that the CPW mode will become leaky and lose energy by radiation of surface waves once the dispersion curve for the lowest surface wave far from the CPW center electrode crosses the dispersion curve for the dominant CPW mode. Lin extended this work to the coplanar stripline case, and showed that the CPS mode is also expected to be leaky [7]. To qualitatively understand the interactions between the relevant modes in our case, we have calculated the dispersion curves for the CPS mode [9] and the surface-wave modes of a grounded dielectric (appropriate under the electrodes) and an ungrounded dielectric (appropriate away from the electrodes); we used a substrate dielectric constant of 13. In all samples, the CPS mode is expected to be leaky at the frequency of the signal we see. Therefore, it is possible to explain the observed oscillatory signal as a surface wave leaked by the leading edge of the CPS signal. However, this explanation does not appear to be able to account for the absence of an observed surface wave in the thinnest sample, where leakage to the lowest transverse electric slab mode TE_0 is expected. In addition, the relative arrival of the surface-wave mode would be expected to depend on substrate thickness but be independent of sampling location. This is not in accord with the CPW observations [6]. Furthermore, while it is difficult from our measurements to quantitatively determine the power propagating in the surface-wave signal, the large amplitudes we see suggest that it is substantial. This is not obviously compatible with the relatively low attenuation due to leakage calculated in [7].

We now turn to an explanation based on direct excitation of surface waves by the photoconductive switch. As mentioned earlier, bulk waves are used in free-space spectroscopy [4]; it seems likely that in our case a similar excitation of propagating and evanescent surface waves occurs. The signals we observe could then be attributed to surface waves that have propagated to the sampling site. The relative arrival time of such signals would be expected to depend upon both substrate thickness and distance from the switch to the measurement location, in agreement with our data and those of [6]. In addition, it is possible to explain the absence of a signal in the thin-substrate case. The calculations of slab modes described earlier show that for a period of 1.5 ps in our thin sample that only the lowest slab mode can propagate under the electrodes, and its effective dielectric constant exceeds that of the other two surface-wave modes in the surrounding dielectric. Therefore, it is plausible that the surface-wave-like mode is excited, and confined under the electrodes in the case of thin substrates. Essentially the surface-wave-like mode is reflected at the outer edges of the electrodes and is effectively guided. Indeed, exactly such an explanation of nulls in the surface-wave leakage in CPW's with finite ground-plane width was given in [8]. These authors explained the nulls as due to resonances in the reflection of surface waves at the outer edges of the ground electrodes. A full calculation of the interactions between the CPS and surface-wave modes, and the possibility of guided surface-wave modes is required.

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