Optical probing of electric fields with an electro-acoustic effect toward integrated circuit diagnosis

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Electro-optic probing of electric fields has been considered as a promising approach for integrated circuit diagnosis. However, the method is subject to relatively weak voltage sensitivity. In this Letter, we solve the problems with electro-acoustic effect. In contrast to the general electro-optic effect, the light phase modulation induced by the acoustic effect is 2 orders of magnitude stronger at its resonant frequency, as we observed in a GaAs thin film probe. Furthermore, this what we believe to be a novel method shows a highly reproducible linearity between the detected signals and the input voltages, which facilitates the voltage calibration.

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Electro-optical probing has been extensively applied to measuring electric fields, particularly that in integrated circuit (IC) troubleshooting [1], on account of its unique merits like high-speed response [2] and low invasiveness [3]. This technique relies on the Pockel effect, also known as the linear electro-optic effect, wherein birefringence is induced in a film [4] or crystal [5] when the film or crystal is exposed to a constant or varying electric field. Traveling through the electro-optical film or crystal whose refractive index varies (Δn) with the applied field, the probing laser beam is delayed ($\Delta\phi$) for the magnitude proportional to the field strength. It is therefore convenient to calculate the field strength exerted to the film or crystal by measuring the phase delay of the probing beam related to a reference beam, or equivalently by measuring the intensity variation if the two beams interfere with each other. If an IC is made of a crystal lacking of inversion symmetry such as GaAs, its internal-node electric signals would be directly deduced by the field-induced refractive index variations of the crystal [6]. Unfortunately, the signal collected by this means is the integration through the entire sample thickness so that the information from a local site of a circuit is difficult to be acquired, provided that the circuit under test is multilayer architected. Particularly, the internal electro-optical probing is difficult to be applied to silicon ICs because of the centrosymmetricity of the crystal structure. To solve this problem, a small piece of electro-optical film or crystal, generally attached to the tip end of a glass cone as a waveguide, is used to sense the field by approaching it to the immediate top surface of a circuit [7,8]. This strategy, called external electro-optical probing, has been proved successful in the silicon IC circuit detection [1].

The current researches on electro-optical probing have been largely focused on high-frequency diagnosis since the Pockel effect allows an ultrawide bandwidth response, far beyond gigahertz [9,10]. Few efforts have been devoted to static or low-frequency detection. Although most of the typical ICs use broadband electronic signals from direct current to hundreds of gigahertz, low frequency or static test is irreplaceable in the IC fault diagnosis and design improvement domains. In this Letter, a low-frequency (0.1–100 kHz) electro-optical probing technology is examined with an expectation to circumvent the effect of high-frequency parasitic parameters. As a result, we find that the field to be detected causes a pronounced change in the thickness (ΔL) of the electro-optical film as the probe due to the electro-acoustic effect [11–13]. In contrast to the Pockel effect, the former increases the sensitivity markedly when it is utilized as an alternating field sensing mechanism at the resonant frequency, which has been experimentally proved effective for instrumentation.

Figure 1 shows the schematic of the probing system based on a cw laser diode instead of a pulse source [14,15], which is generally adopted by the high-frequency probing system. The 1.31 μm output was directed to an objective lens with an NA of 0.4, which focused the light, through a 100 μm diameter tip-ended silica cone as the base of the probe, onto the surface of the circuit to be detected. As the core element, the probe was made by first evaporating a 300 nm indium tin oxide (ITO) thin film functioning as the grounding electrode, on which a $\langle 100\rangle$-cut 50-μm-thick semi-insulating GaAs single crystal film was affixed for field sensing. The light passing through the film and being reflected by the sample surface was utilized as the probe beam, while that reflected by the ITO/GaAs interface was utilized as the reference beam. The interfered light intensity, carrying the information of the relative phase retardation between the two beams, was measured by an InGaAs detector. The use of the ITO grounding film, aiding

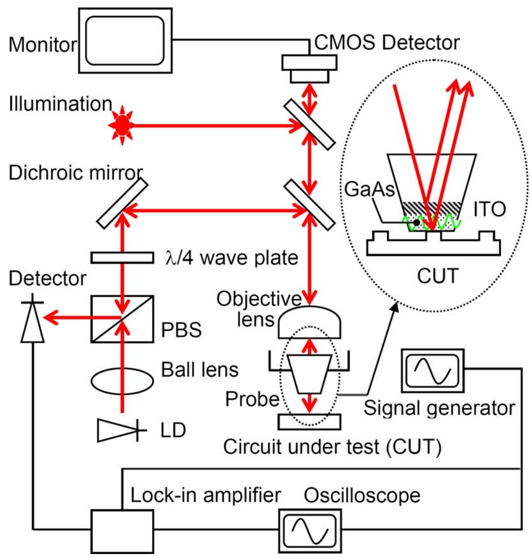

Fig. 1. (Color online) Schematic diagram of the setup for the local electric field detection, where PBS denotes polarization beam splitter. The λ/4 wave plate is 45° oriented with respect to the plane of polarization of the incident probing beam.

the directional alignment of the field from the circuit surface to it, is critical for the precise calibration of the field strength.

The system shown in Fig. 1 was originally designed for electro-optical probing, from which the signal following the field exerted to a sample circuit could be picked up. Surprisingly, at the low-frequency range the modulation signal amplitude became sensitively dependent on the frequency of the applied voltage, with a peak around 8 kHz (Fig. 2). Such a resonant behavior should not arise from the electro-optic effect, known to possess an ultrawide bandwidth response with a constant electro-optic coefficient, e.g., $r_{41} \sim -1.2$ pm/V, from well below the acoustic resonances to far above. The film thickness Δl, besides the refractive index change, also causes the phase retardation $\Delta\phi$. The roles of Δl and Δn are not distinguishable, because the two parameters act together by their product $\Delta n \Delta l$ in changing the light path. Then the problem became how Δl was induced. After an in-depth analysis, the most probable origin was ascribed to the acoustic effect: electrostrictive and inverse piezoelectric effects. The electrostrictive effect is a common property of all dielectrics, caused by the enhanced interaction between oppositely charged material domains or crystalline planes, reducing the material thickness in the direction of the applied field, while the inverse piezoelectric effect creates mechanical deformation upon the application of an electrical field mostly in noncentrosymmetric crystals. The electrostriction effect is a quadratic effect, unlike piezoelectricity, which is a linear effect. This difference is critical to distinguish the two effects.

Whether the assumption was true or not was experimentally examined. The entire probe, with a deadweight of 0.07 g, was directly placed above the circuit surface [inset of Fig. 3(a)]. Different from the case shown in the inset of Fig. 2, where the film itself made an elastic system with the upper end fixed and the lower end free, here the lower end was fixed while the upper end was loaded with the weight of the cone. The resonant peak was therefore much reduced to around 0.56 kHz, far smaller than the former case. The decrease in the resonant frequency f is understandable, since for a typical elastic oscillation system f is associated with its elastic constant K and the mass by $f \sim \sqrt{K/m}$. Actually the reverse square root dependence [Fig. 3(b)] of the resonant frequency on the loading weights, exerted by a series of metal rings, had been attained: the total weights of 0.28, 0.46, 0.73, and 1.16 g led to frequencies of 0.4, 0.26, 0.22, and 0.18 kHz, respectively (Fig. 3). This is a solid proof on the role of the acoustic effect on the resonant peaks.

At high frequency, a GaAs film responds to the excitation of an external electric field by the electro-optic effect, where the acoustic effect is generally more than 1 order smaller and is therefore negligible [16] due to its involvement in the relatively slow mechanical movement of the mass centers of dipole mo-

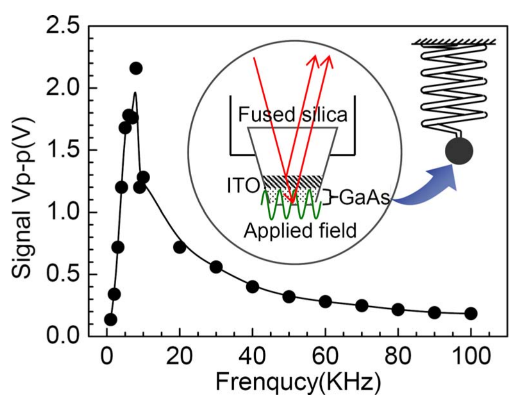

Fig. 2. (Color online) Response of the GaAs film probe to the excitation by an external electric field at low frequency. The inset is an illustration of the probe with the thin GaAs layer fixed to the base on the upper end, while the lower part is freely movable. The oscillation of the GaAs layer is therefore considered equivalent to a simple spring system loaded with its deadweight.

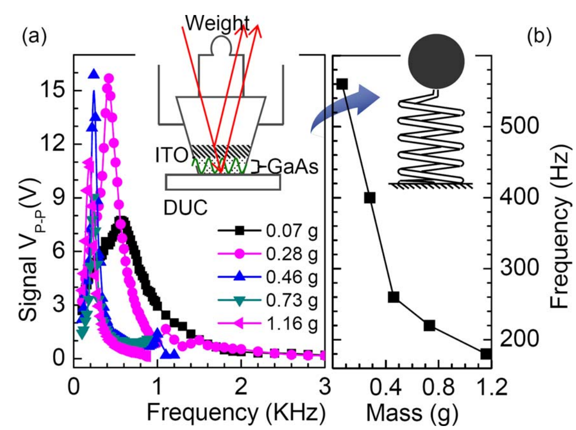

Fig. 3. (Color online) Resonant frequency of the GaAs thin film versus loading weights of 0.07, 0.28, 0.46, 0.73, and 1.16 g. (a) Responsive spectra and (b) loading-weight-dependent resonant peak wavelengths. Oscillation of the film is similar to the case of Fig. 2 but with an increased loading (the weight of the silica base and metal rings).

ments or molecules. Therefore, the acoustic effect dominates at the low frequency of the resonance. Comparing the measured signals, one easily discerns the remarked difference: around $V_{P\text{-}P} \sim 0.1$ V [Fig. 4(a)] at high frequency (50 kHz) and approximately $V_{P\text{-}P} \sim 10$ V [Fig. 4(b)] at low frequency (0.5 kHz) for the identical input voltage. In other words, the sensitivity of the detection may be 2 orders of magnitude enhanced if the acoustic effect is used as a mechanism of the field sensing. An important issue that remains unresolved is the relative weights of the mentioned two effects. The answer has actually been implied in Fig. 4(c): the linear dependence of intensity and the frequency of the measured signal indicate that the inverse piezoelectric effect dominates. Otherwise, the dependence should be quadratic and the detected frequency should be doubled, as the case of unpoled polymer films, where the piezoelectric effect does not occur [17].

The above effect could be utilized as a high sensitivity approach for circuit diagnosis. A purposely designed microstrip circuit as implemented through the current research was loaded with an electric signal of a known voltage, which is adjusted to the resonant frequency of the particular acoustic probe. As a result, the picked signals were linearly dependent on the actually applied voltages with a coefficient determined by the system, and the linearity was highly reproducible for different tips and different circuit samples. Although we found the signal-to-noise ratio in the present detection system insufficient to abstract the useful signal when the applied voltage was reduced to several tens of millivolts, the voltage resolution of the probe was expected to be improved to the sub-millivolt level, which would give rise to a practical solution of low-frequency diagnoses of ICs.

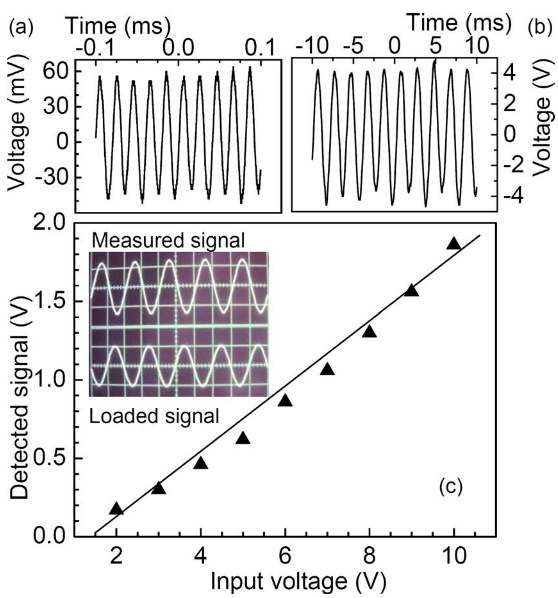

Fig. 4. (Color online) Detection of the electric field above a circuit by a GaAs probe. Waveforms measured at (a) high-frequency (50 kHz) and (b) low-frequency (0.5 kHz) fields. (c) Relation between the signals collected and the voltages applied to the circuit. The inset is a typical oscilloscope screen.

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