Electro-optic Probing: A Laser-Based Solution for Noninvasive High-Speed Testing of Multichip Modules

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Abstract

Electro-optic probing is a proven technique for testing high-speed microwave circuits on substrates such as Gallium Arsenide (GaAs) and Indium Phosphide (InP) by making point-to-point electric field measurements directly in the substrate. The researchers have extended this technique to probe circuit structures on polyimide substrates that would be used for high-density packaging such as Multichip Modules (MCMs). Test results demonstrate the potential to probe circuit structures that are buried in the central layers of an MCM part.

Key words:
Electro-Optics, Electronic Packaging, Polyimide, Testing, Multichip Module (MCM), and Microwaves.

1. Introduction

The ability to perform in situ testing and characterization of both integrated circuits and their interconnecting substrates found in today’s complex multichip packaging structures is becoming increasingly important. Electro-optic probing is a powerful laser-based noninvasive technique that has been used primarily for on-chip testing of high-speed and high-frequency (microwave) circuits. An electro-optic probing instrument is capable of noninvasively making point-to-point electric field measurements internal to microwave circuits instead of only being limited to the information gathered at the input or output ports of a circuit. The technique has been widely demonstrated with semiconductor substrates such as Gallium Arsenide (GaAs) and Indium Phosphide (InP). In this work, the researchers have demonstrated that electro-optic probing to be extremely promising technique for use with polyimide-based substrates. Polyimide, with its low dielectric constant and ease of processing, is an increasingly popular organic polymer used in advanced packaging applications for high-speed circuits such as Multichip Modules (MCMs). This work extends the application of electro-optic probing to circuit structures on polyimide and compares results to the more conventional substrates used for electro-optic probing such as GaAs and InP, demonstrating the potential to noninvasively probe circuit structures that are buried in the central layers of an MCM module.

Electro-optic probing measures the change in the index of refraction of a material due to the introduction of an electric field in the material: the linear electro-optic effect. The linear electro-optic effect was first studied in crystalline solids belonging to crystal classes that lack a center of inversion symmetry. GaAs and InP binary compounds are examples of common semiconductor materials that exhibit this effect. Certain organic polymers, when doped with nonlinear moieties and poled, are also noncentrosymmetric (lack inversion centers) and, hence, exhibit the electro-optic effect. Doped organic polymers are poled by insertion into a strong electric field as the polymer is heated to near its glass transition temperature. The goal of this work is to develop suitable polymers for high-density packaging, such as MCM-Ds, and to show that they can be probed noninvasively by electro-optic probing techniques. Typical polymers that exhibit the electro-optic effect after poling include conditioned photosensitive polymers such as Poly (Methyl...
2. Experimental Configuration

The diagram shown in Figure 1 illustrates the basic set-up for electro-optic probing of the electric field in a test substrate with a high-frequency (RF to microwave, 1 KHz to 10 GHz) signal present in the circuit. The 1300-nm laser source and polarizer in Figure 1 is linearly polarized and oriented at 45° to the y axis of the sample in Figure 1. For a poled polymer, the two orthogonal polarization components of the probe beam are oriented in the z and y directions, so that each experiences a different index of refraction due to the effect of the electric field in the polymer sample. Hence, as shown in Figure 1, the sample may be oriented at a 45° angle to probe for voltage levels in the polymer. The probe beam is linearly polarized and oriented at 45° to the y axis by the half-wave plate, and the applicable electro-optic coefficients are \( r_{31} \) and \( r_{33} \). For GaAs and InP compounds, the \( r_{41} \) electro-optic coefficient is applicable.

![Figure 1. Schematic block diagram of the electro-optic probing instrument for testing polyimide samples.](image)

3. Sample Preparation

To demonstrate electro-optic probing of the polyimide, a series of test samples was fabricated. The test samples were constructed on silicon wafers with the following specifications: p-type, boron doped, (100) orientation, resistivity 25–30 \( \Omega \cdot \text{cm} \) and 14.0–16.0 mm thick. A layer of metal was deposited by sputtering onto the silicon substrate followed by two layers of spun polyimide. Finally, an additional layer of metal was deposited in preparation for poling. The polyimide is Ultradel 9020D doped with 4-(dicyanomethylene)-2-methyl-6-(p-dimethylaminostyrlyl)-4H-pyran (DCM), a nonlinear optical chromophore. The polyimide has 8.4% total solids with 17% DCM by weight. The percent solids are slightly less than for more conventional polyimides where a typical value is 10.5% solids. The silicon wafers are initially prepared on both sides with a 50-nm-thick Cr layer and a 200-nm-thick Al layer. After the Ultradel adhesion promoter A600 is applied, the doped polyimide is static dispensed, spun at 4000 rpm, and then baked at 175°C to set the film. A second layer of polyimide is applied in the same manner, improving the overall integrity and planarity of the substrate. The final polyimide layer thickness was 5.9 \( \mu \text{m} \). After the sample is baked at 175°C to soft cure the polyimide, a 1000-nm-thick Al layer is deposited. The two metal layers act as the electrodes in the poling process. After poling, the top electrode is patterned into circuit structures. The authors chose microstrip transmission lines for the circuit structures.

The poling process consists of heating the polyimide substrate to a final cure temperature that can range up to its glass transition temperature (\( T_g \sim 390°C \)) while subjecting it to a strong electric field to align the chromophores. With the electric field still applied, the samples are cooled to maintain the electric-field-induced alignment of the molecules. These test samples were heated to over 200°C for 20 minutes with an electric field of 300 kv/cm. With the electric...
field still applied, the samples were cooled for 7 minutes. After poling, the top metal layer was patterned and etched using standard photolithographic techniques. Figure 2 shows a cross-sectional representation of the microstrip on a typical polyimide sample. Figure 3 is a scanning electron microscope photomicrograph of the microstrip circuit in a cross-sectional view. The substrates are mounted on an alumina carrier, placed in a microwave test fixture, and inserted in the electro-optic probing instrument. A detailed description of the test mount was previously reported.

The GaAs and InP semiconductor substrates were used to compare previous results with those of the organic polymer reported in this work. These semi-insulating, 450–500 μm thick semiconductor substrates had a Cr/Au base metallization with plated gold transmission lines. A more complete description was previously reported.

4. Test Results

Using the electro-optic probing instrument shown in Figure 1, the polyimide substrates described in the previous section were tested. A signal generator provides the electrical signal to the polyimide samples. The electrical signal, applied to the sample by the signal generator, changes the index of refraction of the sample at the frequency of the applied electric signal. The magnitude of the change in index is proportional to the size of the electro-optic coefficients for the material, with the electro-optic coefficient established by the doping and poling process for the polyimide sample. A 1300-nm diode laser is used to probe the electric field internal to the substrates.

Figure 2. Schematic representation of a typical polyimide test sample.

Figure 3. Scanning electron microscope photo-micrograph of cross-sectional view of polyimide test sample.

Figure 4. Laser probing path for polyimide, GaAs, and InP test samples.

Figure 5. Lock-in amplifier output versus position for an RF signal on a polyimide sample.
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Figure 6. Lock-in amplifier output versus position for an RF signal on a GaAs sample.

Figure 7. Lock-in amplifier output versus position for a 10% duty cycle digital signal.

laser scans across the transmission lines at position (2), the test results show no signal since the laser does not penetrate into the substrates when it is reflected from the circuit metallization on top of the substrates. As expected, there is a strong electric field on each side of the transmission lines that decreases as the scan moves away from each line. The polyimide circuit was also excited with a 10% duty cycle digital signal. Figure 7 shows the electro-optic probing results for a scan across the transmission line using this digital signal.

Figure 8. Calibration curve for a polyimide sample.

5. Discussion

Electro-optic probing of GaAs has been reported with electro-optic coefficients of 1.4 pm/V. The strength of the electro-optic probing signal is dependent on the electro-optic coefficient, the intensity of the laser probe beam, and the thickness of the material. The Ultradel 9020D samples are 5.9 μm thick compared to GaAs samples of 450-500 μm thickness. The Ultradel samples show results with larger signals, but are two orders of magnitude thinner. Hence, a comparison of electro-optic test results for GaAs, InP, and Ultradel 9020D doped with DCM shows an electro-optic effect for the polyimide that is the same order of magnitude as that of the GaAs sample in the 45° test sample orientation. The electro-optic effect can be improved beyond that of GaAs and InP by varying the doping and poling process.

A comparison of the laser probing scans of the GaAs and the polyimide samples, under both RF and digital signal stimulation, shows that the polyimide signals have less spatial extent. This apparent narrowing may be contributed to the high noise levels in the organic samples which obscure measurement of the full extent of the decaying electric field. The larger noise signal also causes small additional perturbations (over the semiconductor case) nearer the transmission line. This added noise in the organic layer case is most likely due to localized laser heating.

Test results demonstrate that electro-optic probing may be used for both analog and digital waveforms on polyimide substrates. The dielectric constant and loss tangent of undoped Ultradel 9020D polyimide are reported as 2.6 and 0.005, respectively, at 1 MHz. Doped Ultradel tested at 1 MHz has a dielectric constant of about 2.6 and a loss tangent of about 0.004. Further testing to 1 GHz shows that the apparent electrical properties of Ultradel 9020D are not changed appreciably up to that frequency. Doped and poled polyimide is currently being tested to determine its electrical properties at frequencies above 1 GHz. Measurement of insertion loss for devices constructed on doped and undoped polyimide shows some increased loss for the doped and poled circuit samples.

The RF signals provided to the microstrip samples ranged up to 60 Vrms. The digital signal had a peak value of 100 V. The calibration curve for a typical polyimide sample in Figure 8 demonstrates that electro-optic probing results are linear with the RF signal reduced to 3 V. Future work will include probing at lower signal levels, which are anticipated to drop below 1 V with the introduction of noise reduction techniques. Buried circuit structures were probed and demonstrated an electro-optic response. These structures are currently being quantitatively evaluated with laser probing scans.
6. Conclusions

Test results demonstrate that electro-optic probing may be used for on-substrate testing of polyimide to determine the electric field. A change in laser light intensity is used to determine the strength and location of the electric field created by the electric signal applied to the probed circuit structures. Many potential applications exist for this noninvasive technique since the laser is able to penetrate the substrates for testing. The researchers have extended this technique to probe circuit structures on polyimide substrates for the first time and demonstrated the potential to probe circuit structures that are buried in the center layers of an MCM part. This information may be used for testing for faults, characterizing circuits, and modeling MCM modules.

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About the authors

Deborah Mechtel was born in Baltimore, Maryland in 1960. She received her B.S.M.E. Degree with high honors from the University of Virginia in 1982. After graduation, she joined Westinghouse Electric Corporation in Baltimore as an Engineer in the Electro-optics Group. She left Westinghouse to join the Ph.D. program of the Electrical and Computer Engineering Department at The Johns Hopkins University. She received a Fellowship for graduate study at The Johns Hopkins University Applied Physics Laboratory and was awarded her Ph.D. Degree in 1994. After graduation, she joined the Electrical Engineering Department at the United States Naval Academy as an Assistant Professor. Her current interests are advanced packaging, electro-optics, and testing of high-speed circuits. Dr. Mechtel is a member of IMAPS, The International Microsystems and Packaging Society, ASEE, and the IEEE Society.

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