NN-4

# TWO-DIMENSIONAL FIELD MAPPING IN MMIC-SUBSTRATES BY ELECTRO-OPTIC SAMPLING TECHNIQUE

W. Mertin, C. Böhm, L. J. Balk*, E. Kubalek

Universität Duisburg, Fachgebiet Werkstoffe der Elektrotechnik, D-4100 Duisburg 1, Germany
*Bergische Universität Wuppertal, Lehrstuhl für Elektronik, D-5600 Wuppertal 1, Germany

## ABSTRACT

For the first time two-dimensional substrate internal field mapping of monolithic microwave integrated structures on GaAs by direct electro-optic sampling is presented. Measurements up to 8.5 GHz have been made. It will be shown that this test technique is very useful for internal function and failure analysis of MMIC.

## INTRODUCTION

Due to the increased understanding of semiconductor physics and due to the steady progress in semiconductor technology, during the last decade electronic devices have been developed possessing switching times in the ps-region and oscillation frequencies above 100 GHz. By monolithic integration of such active devices with passive devices and by integration of different circuit functions multifunction monolithic microwave and millimeter-wave integrated circuits (MMIC) can be produced, now [1].

Detailed knowledge of the internal potential and field distributions is of crucial importance for physical understanding, function and failure analysis, as well as for verification of simulation models of such MMIC [2]. According to typical dimensions of line widths in the range of some micrometer and due to the problems involved with prober testing at very high frequencies only contactless test techniques can be used, such as electron [3] - [5] and laser beam [6] - [8] testing. For analysis of MMIC fabricated on substrates which exhibit the linear electro-optic effect, as e.g. GaAs or InP, direct electro-optic measurement of device-internal electric field can be carried out with superior spatial and temporal resolution [7, 8]. The technique itself is based on the Pockels-effect, i. e. on the change of polarization of a laser beam during its propagation through the substrate due to the influence of the internal electric field. With additional use of picosecond laser pulses and application of sampling technique the local and temporal analysis of integrated circuits in the microwave and millimeter-wave region can be realized.

However, this contactless and non-invasive test technique has been used either for waveform measurements of very fast electric signals at some fixed test points in integrated circuits only [7,8] or for static line measurements [9]. In this paper, for the first time, a test set-up is introduced allowing two-dimensional measurements of internal electric fields with simultaneous picosecond time resolution. For the case of MMIC on GaAs-substrate two-dimensional field measurements up to 8.5 GHz are shown.

## PRINCIPLE OF ELECTRO-OPTIC FIELD MAPPING

For examination of electric fields in the substrate below coplanar waveguides the backside probing geometry as shown in figure 1 is used [8].

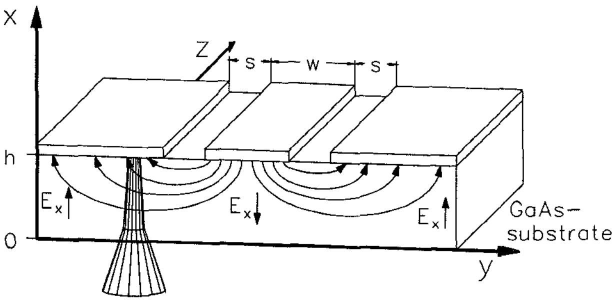


Fig. 1: Backside probing geometry for a coplanar waveguide with directions of the normal components $E_x$ of the electric field. y and z represent the scanning directions of the laser beam.

The local electric field in the substrate changes the optic properties of the GaAs in such a manner that the orthogonal components of a laser beam polarized in the y-z-plane and traveling in the x-direction get a phase retardation of $\Delta\Gamma$. This phase retardation is solely caused by the influence of the electric field component $E_x$ being normal to the device surface. For a roundtrip of the laser beam from the backside of the MMIC to either the ground electrodes or the center electrode and back to the backside the phase retardation is [9]:

$$\Delta\Gamma = (4\pi/\lambda)n_o^3r_{41} \int_{x=0}^{h} E_x(x,y)dx$$

$4\pi n_o^3 r_{41}$ is a constant with $n_o$ the index of refraction in absence of an electric field, $r_{41}$ the linear electro-optic coefficient, and $\lambda$, the wavelength of the laser. The phase retardation can be

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translated into an intensity variation of the detected laser beam after passing a Pockels-cell arrangement. The intensity detected by a photodiode is given by:

$$I(y) \sim \int_{x=0}^{h} E_x(x,y)dx$$

Continuous varying of the laser beam position in respect to the MMIC in y and z direction delivers an intensity distribution being proportional to the normal component $E_x$ of the electric field.

## TEST STRUCTURE AND EXPERIMENTAL SET-UP

The test structure used for the measurements is built up on a 2 x 3 $mm^2$ wide and 410 μm thick semi-insulating GaAs-chip (fig. 2). It is given by a set of coplanar waveguides with a line width of 40 μm and spacing of 26 μm to the outer ground electrodes. The electrodes consist of gold, 3 μm thick, and have an impedance of 50 Ω. For the measurements only the coplanar waveguide 2 within the test structure is used.

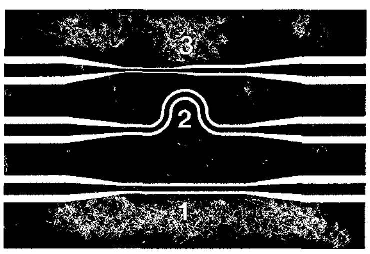


Fig. 2: Layout of the test structure with three different coplanar waveguides based on 410 μm thick s. i. GaAs substrate.

The test structure itself is mounted on a glass carrier on which there are also two 50 Ω coplanar transmission lines. Electric connections to the GaAs-chip are made by bondwires. Finally, at the outer end of the glass carrier there are transitions from coplanar to coaxial transmission lines.

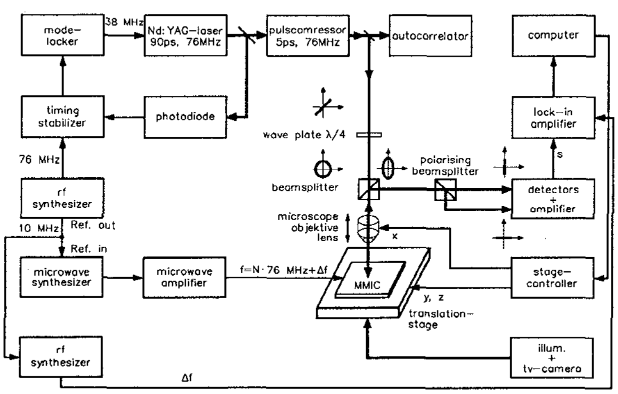


Fig. 3: Experimental set-up for electro-optic field mapping

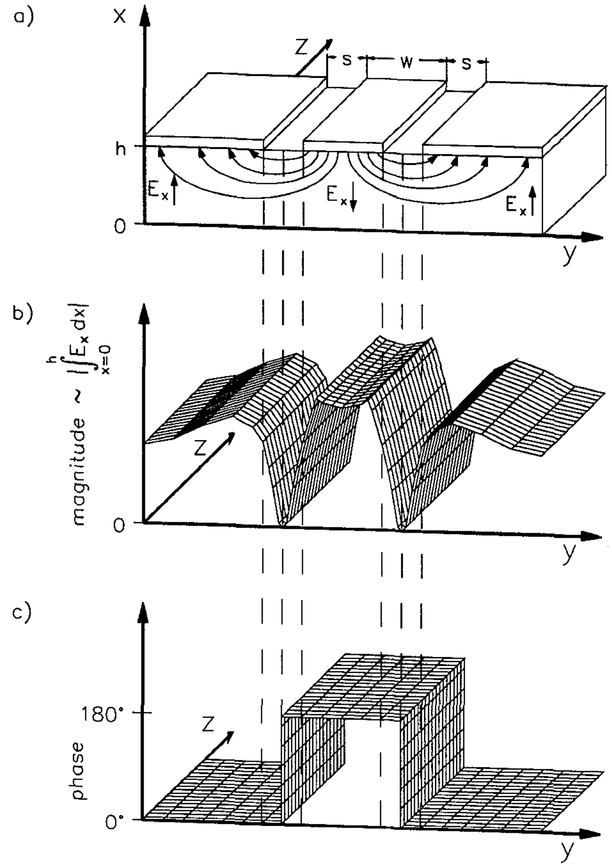


Fig. 4: Schematic description of the expected normal component $E_x$ inside the substrate. (a) tested configuration, (b) expected magnitude distribution proportional to $E_x$, (c) expected direction distribution of $E_x$.

The high frequency experiments are carried out with the experimental set-up as shown in figure 3. The laser beam enters the MMIC from the backside and is reflected either from the center electrode or from the ground electrodes. Two photodiodes detect separately the intensity of the two orthogonal polarization components of the polarized laser beam and the lock-in amplifier measures the difference signal and gives values of magnitude and phase representing the amplitude and direction of the normal component $E_x$ of the electric field within the substrate as sketched schematically in figure 4. For first experiments at low frequencies only the microwave synthesizer and the amplifier are replaced by low frequency components.

## RESULTS

Initially, the performance of the set-up was tested for electric signals of 2 kHz before the application for GHz-frequencies has been made.

*Low frequency measurements:* Figure 5 shows the measured magnitude and phase of the electro-optic signal as a function of the beam position y transversal to the coplanar waveguide for a fixed z-position and for an applied electric signal of 2 kHz.

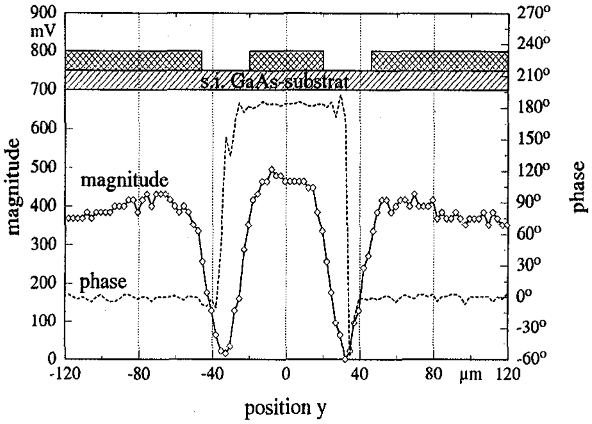


Fig. 5: Measured magnitude and phase of the electro-optic signal (proportional to the electric field $E_x$) as a function of beam position y for a fixed z-position.

Additional scanning in z-direction delivers a two-dimensional distribution of magnitude (fig. 6a) and phase (fig. 6b) as x-modulation images or optionally as gray level images (fig. 7). In both methods of presentation the electric field along the center electrode and the ground electrodes can be clearly seen.

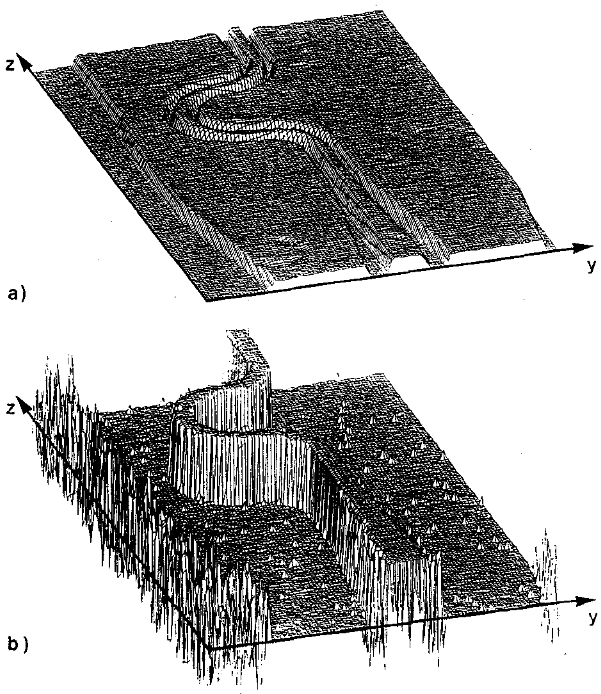


Fig. 6: Measured magnitude (a) and phase (b) of the electro-optic signal as a function of beam position y and z for an electric signal of 2 kHz. The scanned area is 1000 x 1500 $\mu m^2$. The step width is 10 μm.

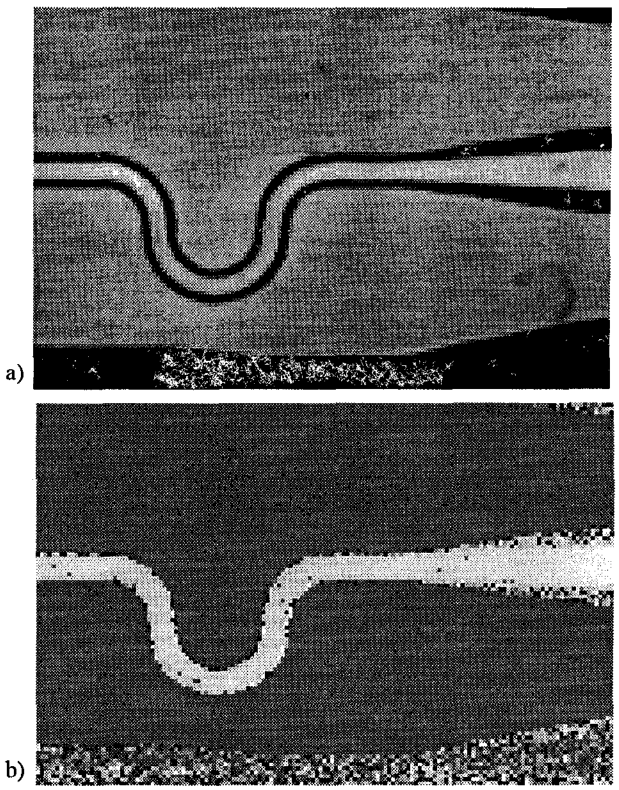


Fig. 7: Measured magnitude (a) and phase (b) of the same electro-optic signal as in fig. 6a, b depicted as gray level image.

*Microwave measurements:* Mapping of high frequent electric fields is demonstrated in figure 8 for the magnitude signal of the same device structure as shown in figure 6 and 7. The operating frequency has been chosen arbitrarily to 8.5 GHz.

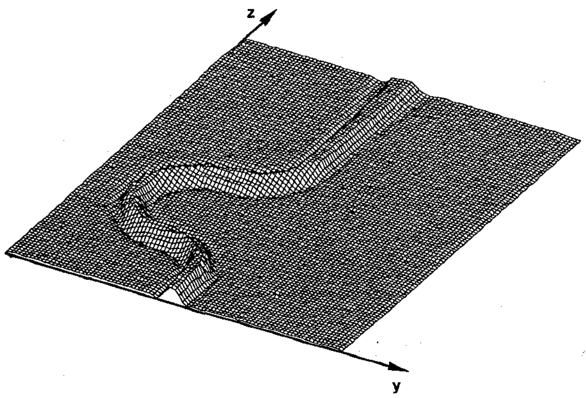


Fig. 8: Measured magnitude of the electro-optic signal as a function of beam position y and z for an electric signal of 8.5 GHz. The scanned area is 1100 x 900 $\mu m^2$. The step width is 1μm.

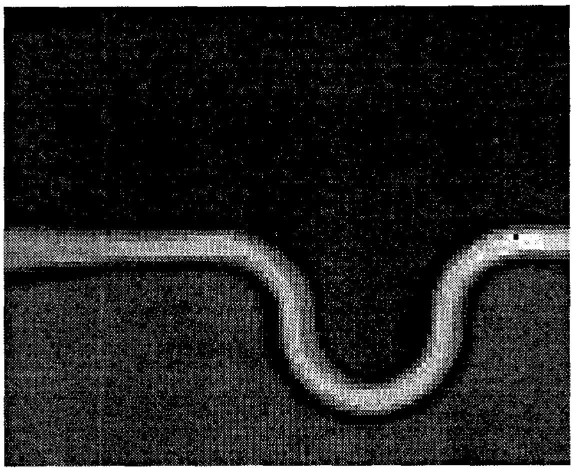

Fig. 9: Measured magnitude of the same electro-optic signal as in fig. 8 depicted as gray level image.

## CONCLUSION

A system for two-dimensional field mapping in MMIC-substrates by using direct electro-optic sampling has been introduced for the first time. Measurements up to 8.5 GHz have been shown.

The main application of the field mapping technique will be the analysis of complex MMIC. The essential of the new test technique is the fact, that due to the small laser beam a high spatial resolution (in the range of some micrometer) and a simultaneous temporal resolution (< 5 ps) can be reached allowing the testing in a contactless and non-invasive manner. It offers a quick survey of the actual internal field distributions thus enabling a control of simulation procedure. Finally, it is evident that by these means easy failure and function analysis within a MMIC can be achieved leading to significant reduction of the otherwise time consuming design/re-design loop.

## ACKNOWLEDGEMENTS

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