

Imaging of large-scale integrated circuits using laser terahertz emission microscopy

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Abstract: We present the redesign and improved performance of the laser terahertz emission microscope (LTEM), which is a potential tool for locating electrical failures in integrated circuits. The LTEM produces an image of the THz waves emitted when the circuit is irradiated by a femtosecond laser; the amplitude of the THz emission is proportional to the local electric field. By redesigning the optical setup and improving the spatial resolution of the system to below 3 μm , we could extend its application to examining of large-scale integration circuits. As example we show the THz emission pattern of the electric field in an 8-bit microprocessor chip under bias voltage.

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References and links

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1. Introduction

Inspection and failure analysis of large-scale integrated (LSI) circuits has become very important, as there is an increasing demand for quality and reliability in integrated circuit chips [1-3]. For an efficient failure analysis of LSI circuits, it is important to localize any electrical failure in the circuits nondestructively before conducting a physical analysis using transmission electron microscopy, electron probe micro-analysis, etc. Several techniques have been developed to localize electrical failures in LSI circuits, such as thermal or infrared emission analysis, laser testing techniques, emission microscopy, and electron beam testing. In particular, laser-testing techniques, such as the infrared-optical beam induced resistance change [4] and optical beam induced current (OBIC) [5], offer alternatives for non-contact, non-destructive failure analysis.

Recently, we proposed using a laser terahertz emission microscope (LTEM) for non-contact, nondestructive inspection of electrical failures in circuits, and demonstrated the localization of a broken line in an operational amplifier [6-8]. Compared with OBIC, a fully non-contact inspection system can be constructed using LTEM because it measures the THz emission in free space from the ultrafast transient photocurrent in a circuit by scanning it with femtosecond (fs) laser pulses. The THz waves can be emitted from areas in the circuits such as photoconductive switch structures with external bias voltage, various unbiased interfaces with built-in electric fields—such as p-n junctions, Schottky contacts (metal/semiconductor interfaces)—or just the surface of semiconductor [9-11]. The THz emission amplitude is proportional to the local electric field in the photo-excited area [12]. By comparing the THz emission images of a normal and damaged chip, the abnormal electrical field resulting from an electrical failure in the circuit can be visualized.

In this study, we completely redesigned the optical setup and succeeded in improving the spatial resolution of the LTEM system to below 3 μm . Consequently we could successfully record THz emission images of an LSI microprocessor under bias voltage.

2. Experimental setup and spatial resolution

Figure 1 shows a schematic diagram of the LTEM system. A mode-locked Er-doped fiber laser (repetition rate 40 MHz, wavelength 790 nm, pulse length 100 fs) is used as the optical source and its beam is split into the pump pulse and the trigger pulse. The beam of the pump pulse (average power 5 mW) is broadened by a beam expander and focused onto the sample surface under normal incidence and the backward THz emission from the sample is collected and guided into the detector.

In the case of the previous system [6], the focused pump pulse had to pass through a hole at the center of the parabola mirror which was used to collect the THz emission. Therefore, the numerical aperture was strongly limited by the long focal length of the focusing lens and the hole size, such as the spatial resolution was about 20 μm . In the present system, the separation of the THz emission from the pump pulse is obtained by a dichroic beam splitter made of an indium tin oxide (ITO) thin film on glass substrate; this film transmits light in the visible range and is highly reflective for the THz waves. The numerical aperture of the present system is only limited by the focusing optics. To focus the pump pulse and collect the backward THz emission, we used an off-axis parabolic mirror because it has no spherical and chromatic aberrations and provides a high collection efficiency of the THz emission. The

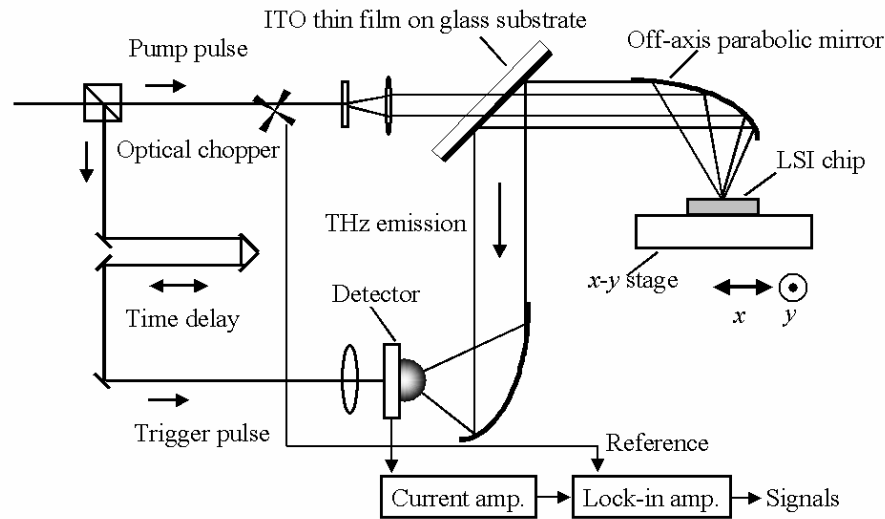


Fig. 1. Schematic diagram of the laser terahertz emission microscope.

effective focal length and the diameter of the parabolic mirror are 50.8 mm and 76.2 mm, respectively.

The THz waves originate from electrical currents owing to the photo-excited electron-hole pairs accelerated by the electric field component parallel to the sample surface (xy plane); the polarization of the THz emission is parallel to the direction of the electric field in the sample. For detection, the optical pulses trigger a low-temperature-grown GaAs (LT-GaAs) photoconductive switch with a bow-tie antenna via an optical time delay (1 ps step). The temporal resolution of the system depends on the photo-excited carrier trapping time (~ 300 fs) in LT-GaAs photoconductive switch which is mainly sensitive for the polarization parallel to x direction. A second scan realized with the sample rotated by 90° allows the measurement of the full electrical field in the xy plane.

The excitation laser pulses are modulated mechanically and the signal synchronized to the laser modulation is detected. By fixing the time delay position at the maximum amplitude of the THz emission, images are acquired by moving the sample under the focused fs laser irradiation. The spatial resolution of the LTEM is limited by the size of the excitation laser spot. Knife-edge measurement shows that the excitation laser spot size at the focal position of the paraboloidal mirror is $2.5 \mu\text{m}$ at full width at half maximum. One of the reasons for this relatively large value is the surface roughness of the off-axis paraboloidal mirror, whose accuracy is up to one wavelength at 630 nm.

To evaluate the spatial resolution, we measured a test sample consisting of several gold line and space patterns on InP substrate. Figure 2(a) shows a schematic of the test pattern. The widths of the lined and spaced in the pattern were 30, 10, 5, 1.5 and $1 \mu\text{m}$. Figure 2(b) shows the line scan profile of the THz emission amplitude from the test pattern under a bias voltage of 1.5 V. THz waves are emitted from the gaps between the gold lines where an electric field exists and the sign of the THz emission amplitude alternates with the direction of the electric field. The smallest pattern for which the THz emission from the electric field could be detected was the $1.5\text{-}\mu\text{m}$ -wide line and space pattern. The temporal waveform of the THz emission and its Fourier spectrum from the $30\text{-}\mu\text{m}$ -wide line and space pattern are shown in (c) and (d). The THz emission has an oscillating waveform due to the resonance effect on the horizontal striplines around 80 ps after the sharp waveform that results from the transient photocurrent at the InP substrate surface. A similar effect was reported on the THz emission

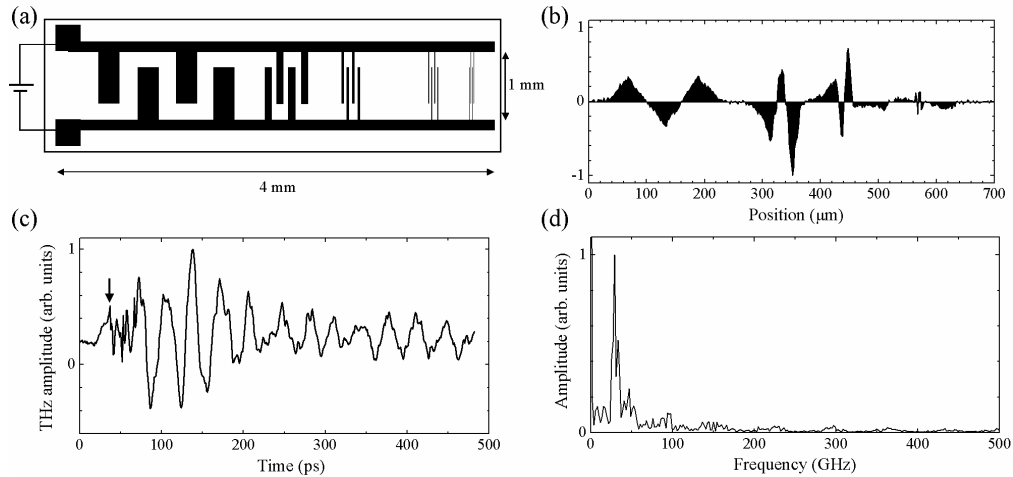


Fig. 2. The widths of the lines and gaps in the test pattern (a) are 30, 10, 5, 1.5 and 1 μm . THz emission profile (b) from the test pattern is obtained by a line scan measurement with fixing the time delay at the position indicated by an arrow in the temporal waveform (c) of the THz emission. (d) The amplitude spectrum of the THz emission from the line and space pattern.

from a photoconductive switch with a log-periodic antenna and explained by the effect of the wave propagation along the antenna edges and its reflection [13].

3. LTEM image of an LSI

We measured an LSI 8-bit microprocessor (custom chip based on the MPU 6502 model supplied by MOS Technologies, Inc.), which has 3- μm -wide interconnection lines. To allow the illumination of the chip from the front, which was covered with a mold, the plastic chip capsule was etched away using chemical agents. Figure 3(a) and 3(b) show the THz emission waveform and its spectrum from the chip under a voltage bias of 3 V. The waveform of the THz emission from the chip is a nearly monocyclic pulse owing to the transient photocurrent, without the oscillation feature that appears in Fig. 2(c), because the interconnection structure is much smaller than the wavelength of the THz emission, limited by the detection bandwidth below 1 THz of our system.

The THz emission image, superimposed on an optical image, is shown in Figure 3(c). The image was obtained using a raster scan over a 5 \times 5 mm area with a pixel size of 10 \times 10 μm . The data acquisition speed was 30 ms/pixel such as the total acquisition time of the image in Fig. 3(c) was about 3 hours; the acquisition time can be shortened to below 20 minutes with acceptable reduction of the signal-to-noise ratio. Although the scanning time is still long for the full inspection of the LSI chips in the production line, we believe it is reasonable for inspecting the failed circuits because the performance of detecting and locating failure spots is more important factor than measurement time in the failure analysis.

The red and blue regions indicate THz emissions with positive and negative amplitudes, respectively, which correspond to the direction of the electric field. In this measurement, the THz emission image was measured by modulating the laser intensity and detecting the polarization in the x direction in Fig. 3(c), so that the resulting image reflects the x direction static electric field considering the modulation frequency (2 kHz) and the lock-in time constant (10 ms).

To evaluate the imaging resolution, Figure 4(a) shows a magnified THz image of a small area in the microprocessor chip, rescanned at a pixel size of 1 \times 1 μm . The cross-sectional distribution of the THz emission image plotted in Fig. 4(b) shows that the details in the THz emission pattern below 3 μm could be observed using the LTEM.

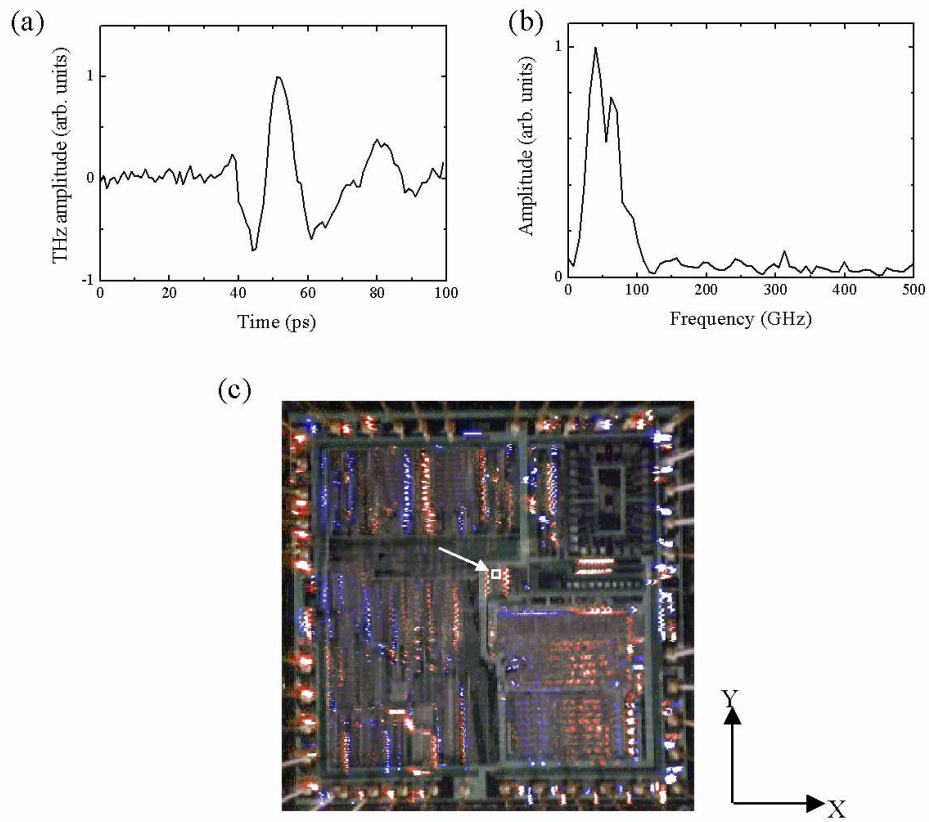


Fig. 3. (a) The temporal waveform of the THz emission from an LSI 8-bit microprocessor chip and (b) its Fourier spectrum. (c) The THz emission image of the microprocessor.

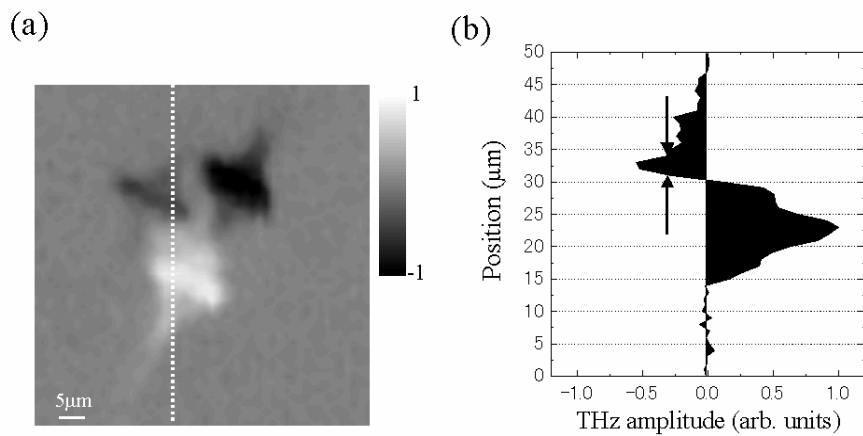


Fig. 4. (a) The magnified THz emission image of the area indicated by the white square in Fig. 3 (c). (b) The cross-sectional distribution of the THz emission image at the dotted line in Fig. 4 (a).

4. Summary

We have redesigned the optical setup of the LTEM and as a consequence were able to improve the spatial resolution by almost one order of magnitude. This allows us to obtain the THz emission image of an LSI microprocessor under bias voltage. At the present stage we can record both components of the electric field vector parallel to the sample surface by rotating the sample. Alternatively we can replace our bow-tie antenna with a spiral antenna detector, which can detect both components of the polarization of the THz emission in xy plane, and use a wire grid polarizer to obtain the two dimensional electric field vector without having to rotate the sample. To detect the internal electric field of the sample in z direction, it is necessary to illuminate the sample at an oblique angle and detect the THz emission along the laser reflection angle.

For the multi-layered LSI circuits, we note that a backside illumination through the semiconductor substrate of the LSI chip is necessary because the multi-level interconnection prevents the generation and detection of the THz emission; this would be the next step towards the development of a non-contact and nondestructive inspection tool in electrical failure analysis.

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