IMAGE OBSERVATION OF PICO SECOND ELECTRICAL PULSE BY SCANNING FORCE OPTOELECTRONIC MICROSCOPE

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ABSTRACT

We succeeded for the first time in visualizing instantaneous voltage distribution of 2ps electrical pulse propagating on coplanar strips (CPS). This result was obtained using a scanning force optoelectronic microscope (SFOEM) which we have developed by coupling a scanning force microscope (SFM) and an ultrafast optical sampling technique. The observed voltage distribution shows a single peak deviating outward. The result seems not consistent with a simple theoretical prediction. There is a possibility that simple theoretical treatments usually used are no more useful for calculating ultrafast pulse distribution.

INTRODUCTION

Recent progress in the semiconductor technology has pushed up speed and density of electronic devices and integrated circuits. This trend seems to continue further up to THz and several 10 nm region in future. In such current situation, ultrafast measurements using a scanning force microscope (SFM)[1-3] or a scanning tunneling microscope (STM)[4-7] have recently attracted a great deal of attention. They are powerful new methods to test ultrafast and ultra-high density electronic devices and circuits. It will be possible by these methods to measure electrical signals at any internal node with sub-ps time and sub-nm spatial resolution. A fundamental idea of the methods of this kind is to introduce an equivalent sampling method into an STM or an SFM by using some kind of sampler or mixer near the probe tip.

We have developed a scanning force optoelectronic microscope (SFOEM) based on an SFM. The SFOEM has a special probe with a conductive sharp tip and a photoconductive semiconductor switch (PCSS)[8] which works as an optical sampler in the so called equivalent sampling measurement.

In this paper, for the first time we report observation of spatial distribution images of electrical pico second pulse propagating on a metal strip and its time evolution by using the SFOEM. This result proves that the SFOEM is very useful to investigate how ultrafast signals propagate in the real world.

SYSTEM SETUP

Figure 1 shows the system setup. The probe is supported by x, y, and z directional piezoelectric actuators. The probe has a photo-conductive semiconductor switch (PCSS) on its thin film cantilever. One of the two electrodes of the PCSS is a sharp probe tip made of Pt, and the other one is connected to a slow pre-amplifier with high input impedance. The cantilever is made of low temperature grown GaAs (LT-GaAs) and the material in the gap region

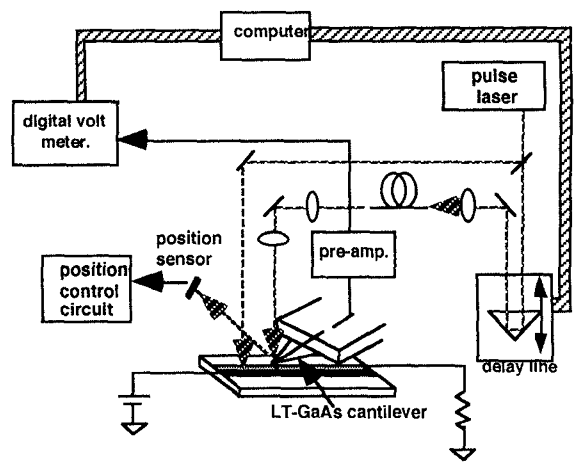


Fig. 1 Schematic of system setup. One laser beam generates electrical pulse train. The other beam turns on optical switch on the probe.

between the two electrodes works as the PCSS. An ultra-short optical pulse train from a mode locked Ti: sapphire laser is used to turn on and off the PCSS. When an electrical signal of a device under test (DUT) is repetitive and the period is synchronized to that of the laser pulse train, the DC voltage after the PCSS reproduces an instantaneous signal voltage. By scanning the optical path length, the ultra-fast signal waveform is accurately measured. It is so called equivalent sampling method, and is similar to the principle of a high speed sampling oscilloscope or a strobo camera.

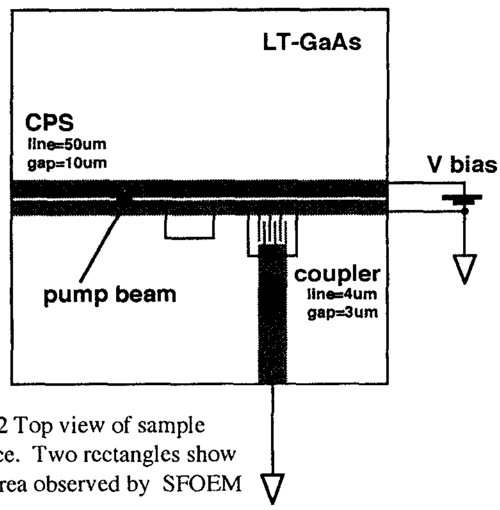


Fig. 2 Top view of sample device. Two rectangles show the area observed by SFOEM

In this measurement the DUT is DC biased coplanar strips (CPS) fabricated on a LT-GaAs layer on a semi-insulating GaAs substrate illustrated in figure 2. There is one more strip connected to the CPS ground strip via an interdigit coupler. We generated electrical pulses by illuminating the gap region of the CPS, and measured the electrical pulses in the areas on the ground strip and the interdigit coupler shown by rectangles in figure 2. The incident optical pulse has 100fs duration, 80MHz repetition rate , and 830nm wavelength.

A probe beam separated from the pump beam is introduced to the SFOEM head through a single mode optical fiber and focused onto the PCSS on the probe. The average beam power at the probe is 10mW. 70% of the incident beam is used to turn on the PCSS and the other 30% is reflected to a beam position detector. The output from the detector is used for probe position control. The probe position control procedure is the same as that of a normal SFM. That is, the z directional piezoelectric actuator controls the probe height so that the reflected beam spot is maintained at a fixed position on the detector using a feedback circuit. Since the deviation of the reflected beam position corresponds to a deflection of the cantilever, the deflection and the force between the probe tip and the DUT surface are also maintained constant.

Although an ordinary SFM uses a CW laser beam to detect the probe position, we use just one pulse beam for both the probe position control and PCSS switching. Since the periodic frequency of the optical pulse train is sufficiently higher than the bandwidth of the position control circuit, the pulse beam operation causes no disturbance to probe position control. In this situation, by scanning the x and y directional piezoelectric actuators we observed instantaneous potential distribution.

PROBE FABRICATION

We used low temperature GaAs (LT-GaAs) for the material of the probe[9]. This material is photoconductive and the photo-excited carriers have extremely short life time[10,11]. This property is preferable for the material of an ultrafast PCSS. Figure 3 shows a SEM picture of the bottom side of the SFOEM probe. The base and the height of the triangle cantilever are 200μm for the both, and the thickness is 1μm. There are a Pt tip electrode on the top of the pyramidal protrusion and a Pt lead on the cantilever. The base and the height of the pyramid are 18μm and 13μm respectively. Since there is a gap between the tip metal and the lead, this region works as a PCSS when illuminated by an optical pulse.

The LT-GaAs cantilever including the PCSS was grown on a Si substrate using molecular beam epitaxy and the Si substrate under the cantilever region was removed in the final process. Growth temperature was 300 °C. After a 1μm growth, the wafer was annealed at 600 °C for 10 min.

Mechanical strength and flexibility of the cantilever is good enough to bend more than 60 deg. Therefore the SFOEM probe is rarely broken and is very easy to treat. Calculated force sensitivity of the probe is 0.3N/m. The

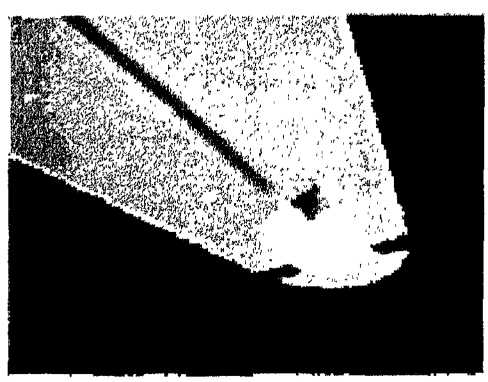


Fig. 3 Bottom view of probe. Cantilever and pyramidal protrusion are made of LT-GaAs thin film

force between the probe tip and the DUT is in the order of nN, which is too small to cause any damage to the DUT surface.

PROPAGATING PULSE ON A STRIP

In figure 4, we show three sequential images observed with 0.8ps interval. The observed area is 80μm x 68μm on the ground strip (Fig. 2). There is the biased strip above this area. There is a single pulse propagating from left to right. The color bar at the bottom of figure 4 shows how each color corresponds to each voltage. The peak voltage is 40mV and the propagating velocity is about 40% of the light velocity, which is consistent to the dielectric constant of the GaAs substrate.

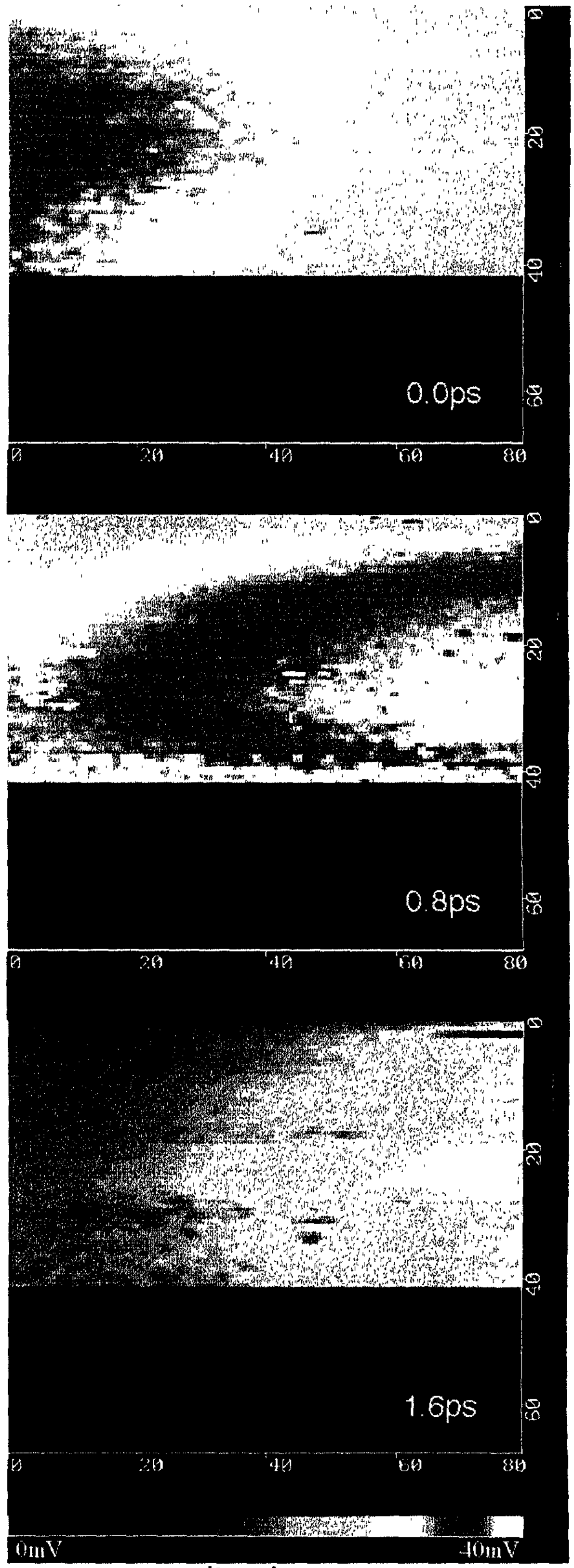
Although people may expect linear wavefront or single peak standing aside toward the gap, the observed images show single peak standing aside toward the opposite side. This result seems not consistent to ideal mode of propagating electromagnetic wave. This inconsistence might be derived from invasiveness due to the existence of the probe itself. However, the probe tip would be too small to cause such significant deviation.

In ideal coplanar strips with infinite conductance, there is no magnetic field perpendicular to the strip surface. However, the real strip has a finite conductance which causes a finite skin depth and magnetic field perpendicular to the strip surface. Those would be responsible for the observed result. If the observed image represents actual potential distribution, it means that simple theoretical treatments usually used are no more useful for calculating ultrafast pulse distribution and SFOEM measurements will be much more important. In order to make clear these possibility, some simulation works are needed.

INTERDIGIT COUPLER

Fig. 5 shows a topographic image and an instantaneous potential image observed in the 80μm square area around the interdigit coupler. A 2ps pulse is just propagating near the coupler. Each finger has 4μm width and 46μm length. The gap is 3μm width. The color bar at the bottom of each image shows how each color corresponds to each geometric height or voltage.

In the potential image, small waves with a short period have no meaning because it is due to a 50Hz noise from a power line. Upper electrode has higher potential and lower one has lower potential. In the GaAs substrate area between metal fingers, measured potential has no meaning. Because the substrate is insulator, the charge sampled at previous metallic point is maintained for a short time. In this measurement, the probe scans from left to right. Therefore the substrate region of the potential image in figure 5



vltage image

Fig. 4 measured potential distribution on metal strip

0-7803-4603-6/97/$5.00 (c) IEEE

seems as if it had a potential the same as the left metal finger.

The SFOEM is able to move the probe position anywhere in the observed area. We measured time evolution of potential at three points labeled A, B, and C in figure 5. Figure 6 shows the results. The curve B seems to include differential component of curve A. It is reasonable because the two electrodes have capacitive coupling. The curve C is almost similar to B. However, C is slightly smooth rather than B. As seen above, The SFOEM can measure potential time evolution at any point with interest with ps time resolution and sub micron spatial resolution.

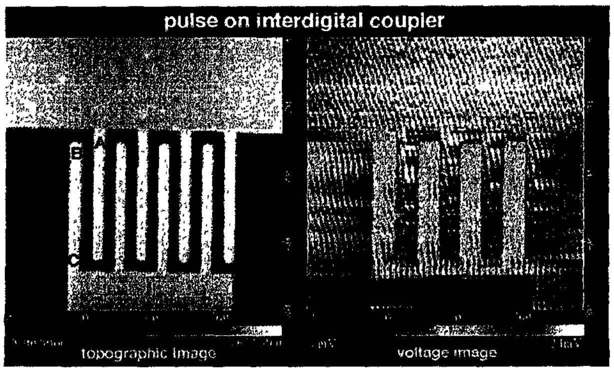


Fig. 5 Simultaneously bserved images of interdigit coupler. Left is topographic image. Right is potential image.

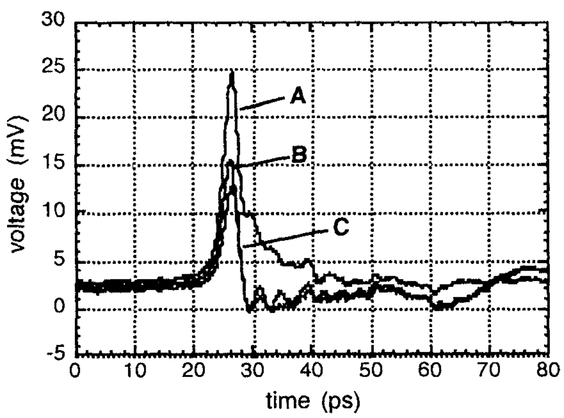


Fig. 6 Time evolution of pulse voltage measured at fixed point. Each label corresponds to the position with the same letter in Fig. 5.

SUMMARY

We succeeded for the first time in visualizing instantaneous potential distribution of 2ps propagating pulses using the SFOEM. Additionally we demonstrated that the SFOEM is able to measure time evolution of such ultrafast signals at any internal point of devices. The obtained images showed single peak standing aside which seems inconsistent to normal theoretical expectation for ideal strips. The result means that the SFOEM measurement will be much more important for ultrafast electrical signal measurement.

REFERENCES

[1] A. S. Hou, F. Ho, and D. M. Bloom, "Picosecond electrical sampling using a scanning force microscope," Electron. Letters Vol. 28, no. 25, pp. 2302-2303 (1992)

[2] C.Boehm, F Saurenbach, P Taschner, C Roths and E Kubalek, "Voltage contrast in integrated circuits with 100nm spatial resolution by scanning force microscopy", J. Phys. D: Appl. Phys. 26, pp.1801-1805 (1993)

[3] John Nees and Douglas Craig, "Laser-diode based scanning force microscope and ultrafast sampling probe", technical digest 1995 Ultrafast electronics and optoelectronics, Dana Point, CA, Vol.13, pp.172-174 (1995)

[4] K. Takeuchi and Y. Kasahara, "High-speed optical sampling measurement of electrical wave form using a scanning tunneling microscope," Appl. Phys. Lett. Vol. 63, no. 26, pp. 3548-3549 (1993)

[5] K. Takeuchi, A.Mizuhara and Y. Kasahara, "Application of scanning tunneling microscope to high-speed optical sampling measurement", IEEE trans. instrumentation and measurement, Vol.44, No.3, pp.815-818 (1995)

[6] G. Nunes, Jr. and M. R. Freeman, "Picosecond resolution in scanning tunneling microscopy," Science Vol. 262, pp1029 (1993)

[7] S. Weiss, D. F. Ogletree, D. Botkin, M. Salmeron, and D. S. Chemla, "Ultrafast scanning probe microscopy," Appl. Phys. Lett. Vol. 63, no. 18, pp. 2567-2569 (1993)

[8] D. H. Auston, "Picosecond Photoconductivity: High-Speed Measurements of Devices and Materials," in Measurement of High-speed Signals in Solid State Devices, R. B. Marcus, Ed., San Diego, CA: Academic Press, chapter 3, pp. 85-134 (1990)

[9] K. Takeuchi and A. Mizuhara, "Low-Temperature grown GaAs probe for ultrafast electrical signal measurement," Electron. Lett. Vol. 33, no. 4, pp. 325-326(1993)

[10] S. Gupta, M. Y. Frankel, J. A. Valdmanis, J. F. Whitaker, G. A. Mourou, F. W. Smith, and A. R. Calawa, "Subpicosecond carrier lifetime in GaAs grown by molecular beam epitaxy at low temperatures," Appl. Phys. Lett. Vol. 59, no. 25, pp. 327 (1991)

[11] N. Atique, E. S Harmon, J. C. P. Chang, J . M. Woodall, M. R. Melloch and N. Otsuka, "Electrical and structurl properties of Be- and Si-doped low-temperature-grown GaAs", J. Appl. Phys., 77, (4), pp. 1471-1476 (1995)