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Ultrafast Photoconductive Switches with a 43 nm Gap Fabricated by an Atomic Force Microscope

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The oxidation process using an atomic force microscope was applied for ultrafast metal-semiconductor-metal photoconductive switches. The photoconductive gap was formed by the oxidation of 4 nm thick titanium layer. The photoconductive gap is 43 nm wide and covered with the oxidized titanium. The oxidized titanium is not only a good insulator but also transparent for the excitation beam. The full width at half maximum response of 770 fs for the transverse component of electric field was obtained at the bias voltage of 6V.

I. INTRODUCTION

Metal-semiconductor-metal photoconductive switches have been developed as fast photodetectors. Ultrafast response of the switches has been achieved by reducing carrier lifetime using low temperature grown substrates, or by a narrow photoconductive gap fabricated by electron-beam lithography. The impulse response of 0.87 ps, has been reported for a photoconductive switch with a gap of 300 nm using a low temperature grown GaAs substrate made by electron beam lithography[1]. Photoconductive switches with a gap of 100 nm has also been fabricated[1], though the response gets slower due to the intrinsic CR time constant.

The fabrication of semiconductor nano-structures based on a scanning tunneling microscope (STM) or an atomic force microscope (AFM) has been proposed[2] and applied for various devices such as metal-insulator-metal diodes[3] and single electron transistors[4]. The probe process has been also applied for optoelectronic devices[5]. We have reported the ultrafast response of photoconductive switches with a gap of 100 nm by oxidizing a titanium thin film using an AFM[5].

In this paper, we present the fabrication process and the characteristics of a photoconductive switch with a gap of 43 nm. This switch has the narrowest gap, to our knowledge. The fast response of the ultrafast switch was measured by an electrooptic(EO) sampling system which has been proposed[6] and developed[7] as a promising technique for electrical signals in femtosecond region.

II. FABRICATION PROCESS

The sample was set in an air-ambient AFM after the deposition of a 4 nm thick titanium layer on an unintentionally doped semi-insulating GaAs substrate(Fig. 1). The oxide line was formed by moving the cantilever biased negatively to the sample. We can control the width and the thickness of a oxide titanium line by scanning speed and bias voltage between a sample and a cantilever of an AFM. We made a 43 nm-oxide titanium line at scanning speed of 10 nm/s and the bias voltage of 8 V. The relation between the dark current and the bias voltage is shown in Fig. 2. The resistance is 2 MΩ at low bias condition, and is 773 kΩ at the bias voltage of 2 V. The resistance is smaller than the reported value of 10 MΩ for the photoconducvive switch with a gap of 100 nm. The decrease of Schottkey-barrier height is enhanced due to the strong electric field between the electrode at the same bias condition compared to a 100 nm-gap-switch. The break down didn't occur at the bias voltage of 10 V. It is plausible that the insulator prevent the break down along the semiconductor surface or through the air gap between the electrodes. The excess capacitance due to the oxidized titanium is calculated to be 0.14 fF from the measured dielectric constant(ε_r = 24)[3], which is much smaller than the capacitance caused by the GaAs substrate. This oxide wire is not only transparent to the excitation beam but also a good insulator. After the oxidization, we formed coplanar transmission lines. The transmission lines were made of Ti / Au, and they were 10 μm wide and 200 nm thick.

The line separation was 10 μm. We removed the excess titanium thin film except for the part of the photoconductive switch by reactive ion etching.

III. EO SAMPLING SYSTEM

The fast response of the switch was measured by an EO sampling system based on a colliding pulse mode-locked (CPM) dye laser. The laser provides a 60 fs optical pulse train (λ=620 nm) at a repetition rate of 94.2 MHz. The output power was 10 mW, and the laser beam was divided into the excitation beam for the switching and a probe beam for the measurement. The polarization of the probe beam is controlled by the waveplate to estimate two vector components of electric field[7]. The device under test is depicted in Fig. 3. The probe beam passes through the probe crystal and is reflected at its bottom by the dielectric mirror deposited on the probe crystal. The probe crystal is made of 50 μm-thick $LiTaO_3$ and whose x axis is perpendicular to the surface of the sample. This configuration has sensitivity both to the direction along y axis and z axis of the probe crystal. The sensitivity for the electric field along y axis is proportional to the eletrooptic coefficient r_{22} (1 pm/V) and the sensitivity for the electric field along z axis is proportional to the coefficient (r_{33}-r_{13}) (27.9 pm/V). The reflected beam through a compensator which compensate static retardation, was decomposed into two polarizing components, and they were detected by two slow Si photodetectors. The electrical output signal was measured through a lock-in amplifier. The time resolution of the system is determined by the optical pulsewidth(40 fs), the spot size(< 5 μm) of the sampling beam and the electrooptic probe size. We estimated the time resolution of the whole system to be less than 200 fs.

IV. RESULTS AND DISCUSSION

The impulse response of the switch was measured at the point 70 μm from the switch. The applied bias voltage was 6 V. A full width at half maximum is 790 fs(Fig.4). The output signal contains not only transverse component of electric field and also longitudinal component of electric field. The mixing of the longitudinal component is due to the deviation from the designed cutting or alignment of an electrooptic probe crystal, and non-TEM-mode components which cannot be ignored in high frequency region. The longitudinal component of electric field has been observed[7] for the electrical signals in femtosecond region. We can estimate the longitudinal and the transverse component by the method of the polarization control of EO sampling[7].

The transverse and the longitudinal component of the electric field is shown in Fig. 5. The pulse width for transverse component is 770 fs. The deference of 3 % from the measured value is due to the longitudinal component. The peak intensity is 15 % smaller than the measured value. To estimate a waveform of electrical signals in femtosecond region, it is inevitable to remove a longitudinal component of electric field. The longitudinal component cannot be observed at the region of slow tail of the transverse component. The peak intensity of the longitudinal component is 20 % of the peak intensity of the transverse component.

V. CONCLUSION

Ultrafast photoconductive switch with a gap of 43 nm was fabricated through the oxidation process by controlling the scanning speed of a cantilever and the bias voltage between the cantilever and the sample. We can apply the bias voltage more than 6 V which corresponds to the electric field of 1.4 x 10^3 kV/cm at the surface of GaAs substrate. The dark current increases at a high bias condition due to the decrease of Shottkey-barrier height by the strong electric field. It is plausible to explain the fast response of the switch by the velocity overshoot in such a strong electric field. The full width at half maximum of 770 fs for the impulse response were obtained for the bias voltage of 6V at the distance of 70 μm from the gap. Fast response in femtosecond region has been achieved for the photoconductive switch with a narrowest gap, to our knowledge.

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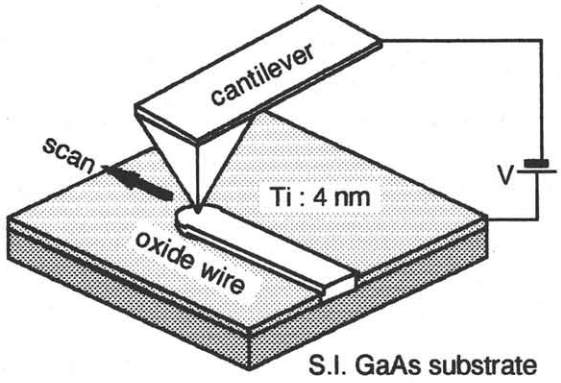

Fig. 1 The schematic view of the oxidation process of a titanium thin film by an atomic force microscope

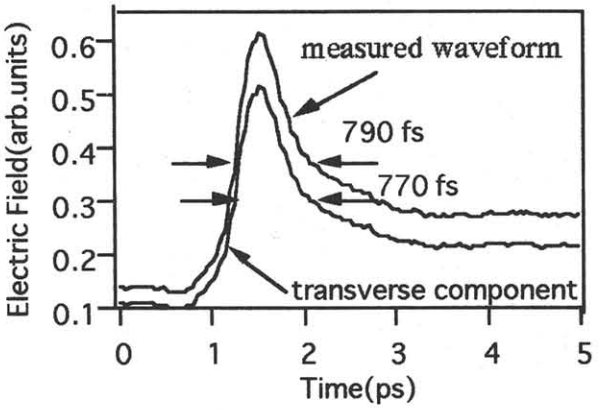

Fig. 4 The output signal from the 43 nm gap photoconductive switch measured by an electrooptic sampling system

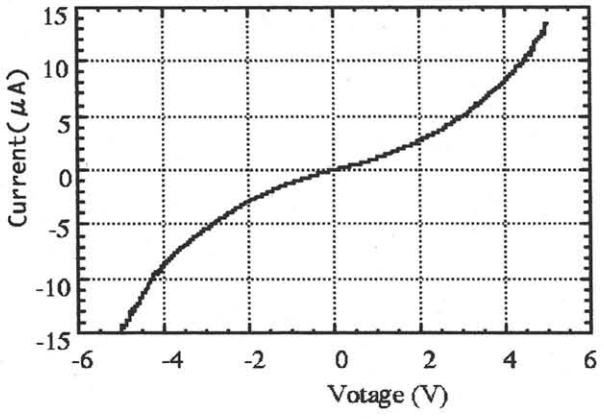

Fig. 2 I - V characteristic for the photoconductive switch

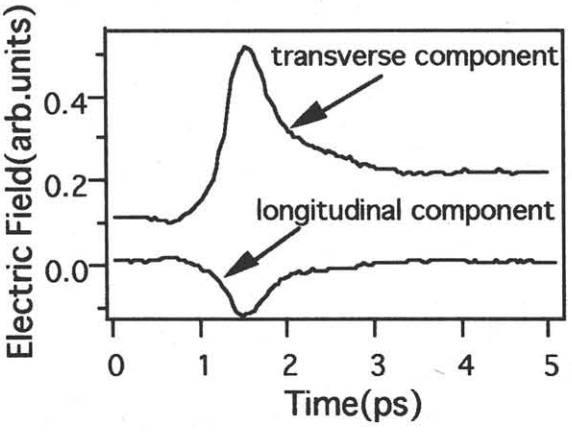

Fig. 5 The transverse and the longitudinal component of impulse response of the 43 nm-gap-photoconductive switch estimated by the polarization controlled EO sampling system

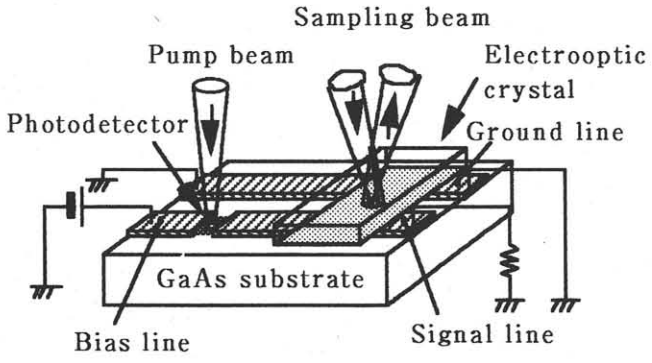

Fig. 3 The configuration between an electrooptic probe and a device under test