THz Generation from Photoconductive Switches with Naonostructures

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1. Introduction

We have developed photoconductive switches for use as fast photodetectors and signal sources of THz radiation. There are two approaches to achieve ultrafast response of such photoconductive switches. One approach is to reduce the carrier recombination time by low-temperature-grown-GaAs[1,2] or ion-implantation[3]. A recombination time of less than 1ps has been achieved[1,2,3] though most photo-excited carriers recombine and are not taken out as electrical signals. The other approach is to reduce carrier transit time by the formation of a narrow photoconductive gap. Nanoscale lithography has played an important role in achieving ultrafast response of the switches. We have proposed and realized a structure of insulator-gap photoconductive switches[4], which we fabricated by using an atomic force microscope (AFM). To obtain ultrafast signals from photo-conductive switches, we found it necessary to integrate with a transmission line or with an antenna structure. Photoconductive switches with transmission lines convert optical pulses to transmission modes, and photoconductive switches with antenna structures convert optical pulses to radiation modes. In this paper, we will present our fabrication process for the insulator-gap photoconductive switches and characterization for transmission modes by the electro-optic(EO) sampling.

2. Fabrication Process

The fabrication of semiconductor nano-structures using a scanning tunneling microscope(STM) or an atomic force microscope(AFM) has also been developing rapidly. We have fabricated[5,6] photoconductive switches by oxidizing a thin titanium film using an AFM, which is a recently proposed[7] and developed[8] method. We set the sample in an air-ambient AFM after the deposition of a 4-nm-thick titanium layer on an unintentionally doped semi-insulating GaAs substrate. We formed the titanium layer by electron beam heating at a pressure of $2x10^{-7}$ Torr. We formed the oxide line by moving the cantilever, the bias voltage of which is negative to the sample(Fig.1).

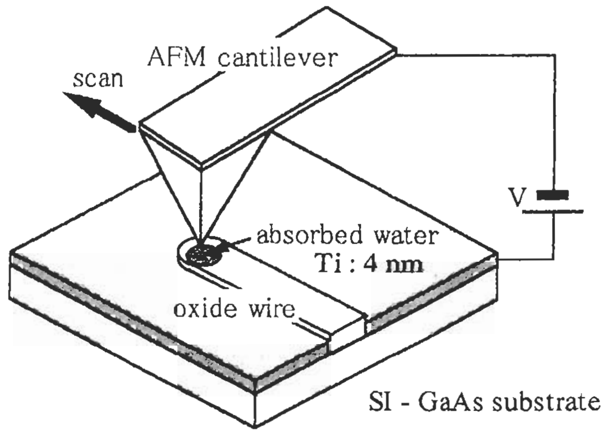

Fig.1 Oxidation of a titanium thin film using an atomic force microscope

We induced oxidation of the titanium by the process of the anodization, due to absorbed water between a AFM probe and the titanium surface. We can control the width and the thickness of the titanium oxide wire by adjusting the scanning speed and the bias voltage between the sample and the cantilever. This oxide wire acts as an optical window and an insulator between the titanium electrodes. We have made photoconductive switches with a gap of 43 nm and 100 nm. We also made 12 lines of titanium oxide to form multiple photoconductive gaps in series. The oxide wire width is 300 nm, and the lines are separated by 200 nm for the multi-gap switch. After the oxidization, a 200-nm-thick Ti/Au coplanar transmission lines were formed. We removed the extraneous titanium between the striplines by reactive ion etching, using SF_6 gas. Our fabrication process for the switch is shown in Fig. 2. The relation between the dark current and the bias voltage is shown in Fig. 3. The dark current for the multi-gap sample at the bias voltage of 2V is 8.0 nA, which is much smaller than the dark current of 200 nA for the 100-nm-gap sample. We found that breakdown did not occur at a bias voltage of 10 V. It is plausible to assume that the insulator prevented the breakdown between the electrodes. The increase of the dark current for the 43 nm-gap photocon-

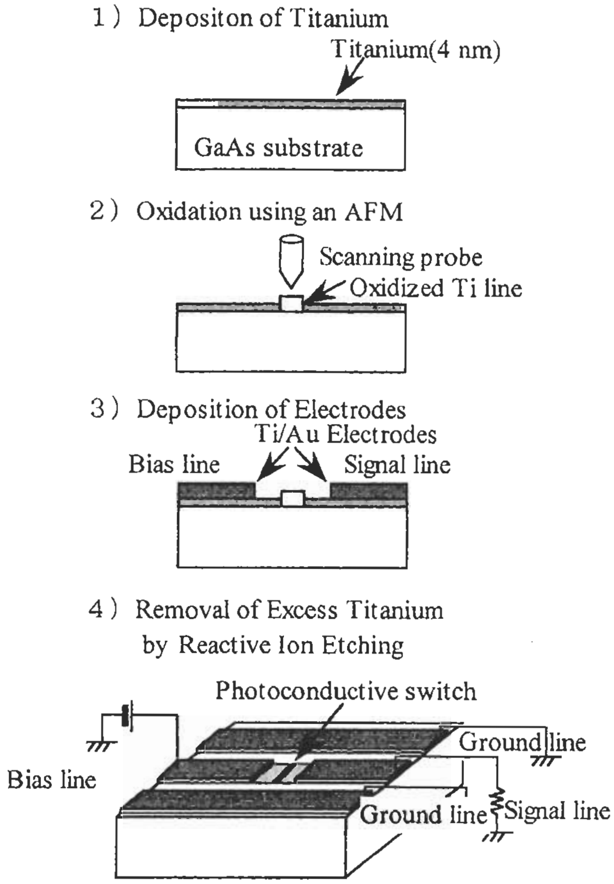

Fig.2 Fabrication Process

ductive switch occurs because of the enhancement of the decrease of Schottky-barrier height, due to the stronger electric field between the electrodes at the same bias condition when compared to the other switches. We also found that breakdown did not occur at a bias voltage of 10 V for the 100-nm-gap sample. It is also plausible to assume in this case that the insulator prevented the

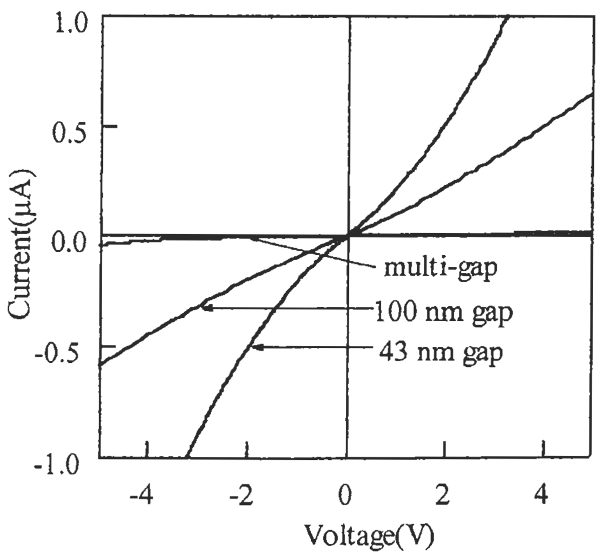

Fig.3 The relation between the dark current and the bias voltage

breakdown or a discharge between the electrodes. The dark current for the multi-gap structure is dramatically reduced.

3. Masurement for the Photoconuctive Switches

We measured the ultrafast response of the switch by the EO sampling[9]. EO sampling senses the electric field in a EO crystal such as $LiNbO_3$ which is placed close to a device under test. We put the EO probe more than 50 μm away from the gap to measure transmission modes without including radiation modes. We determined the time resolution of our EO sampling system by the optical pulse width (60 fs), the spot size (<5 μm) of the sampling beam, and the transit time of the optical pulses passing through the probe crystal.

The laser provides 60 fs optical pulse train at a repetition rate of 94.2 MHz, with an output power of 10 mW. The output beam is divided into a pump beam and a sampling beam at the ratio of 9:1. We focused the pump beam on a photocondutive switch through the transparent EO crystal. Part of the crystal is coated by a dielectric mirror at the bottom, and is used as an EO probe. A 1/2 waveplate and a polarizer control the polarization of the sampling beam. The sampling beam goes through the probe, and is reflected at the bottom. The configuration between the probe and the device under test is depicted in Fig.4. The reflected beam at the probe goes through the compensator and is decom-posed, at the polarizing beam splitter, into two polarizing components, which make an angle of 45° to the principle axes of the probe crystal. We detected these two beams are detected by two Si photodetectors.

We measured the impulse response from the 100-nm-gap switch at a point 70μm from the switch. We did not observe the radiation modes, since the sampling point is sufficiently far from the switch. The output signal contains both the

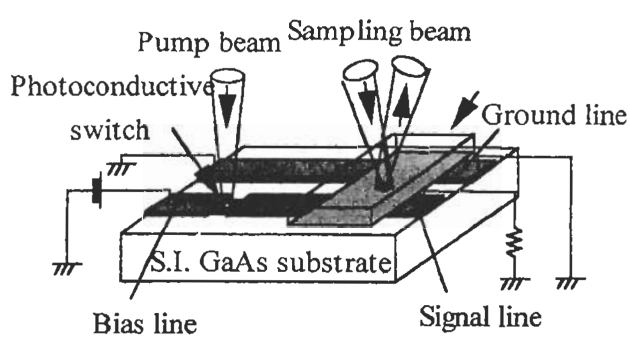

Fig.4 Device under test

transverse and longitudinal components of the electric field. We found that the mixing of the longitudinal component is caused by the deviation from the designed cutting or alignment of an EO probe crystal and the non-TEM-mode components, which cannot be ignored in the high-frequency region. We obtained the transverse electric field by subtracting the influence of the longitudinal component. The transverse and longitudinal components of the electric field are also shown in Fig.5. The pulsewidth for the transverse component is 437 fs. The difference of 6 % from the measured value is caused by the longitudinal component. The peak intensity is two times higher than the measured value. The slow decay after the electron current due to the velocity overshoot includes the hole current and probably the electron current, photoexcited deep inside the substrate. To obtain an accurate waveform of electrical signals in the femtosecond region, we found it necessary to remove the longitudinal component of the electric field. The longitudinal component cannot be observed at the region of the slow tail of the transverse component. The peak intensity of the longitudinal component is 20% of the peak intensity of the transverse component. We have shown experimentally that the electrical waveform was no longer expressed by simple TEM modes because of the significant appearance of the longitudinal electric field. We have demonstrated that exact estimation of the width and the rise time of short electrical pulses could only be achieved by compensating for the longitudinal component.

5. Summary

We fabricated ultrafast photoconductive switches through an oxidation process by controlling the scanning speed of a cantilever and the bias voltage between the cantilever and

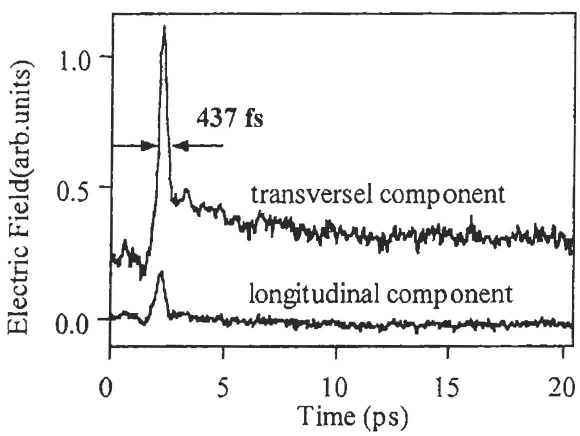

Fig.5 The longitudinal and transverse component of the electric field

the sample. It is plausible to assume that the fast response of the switch was due to the velocity overshoot in such a strong electric field. We estimated the intrinsic response of the switch to be 210 fs based on the results of measurement of the propagation of the electrical signals. We attributed the slow decay after this fast response to the hole current and the electron current absorbed deep inside the substrate. The output signal contains both the transverse and longitudinal components of the electric field. The mixing of the longitudinal component is caused by the deviation from the designed cutting or alignment of an EO probe crystal and the non-TEM-mode components which cannot be ignored in the THz region. We have observed the longitudinal component of the electric field for the electrical signals in the THz region. We can estimate the longitudinal and the transverse components via the polarization control of the EO sampling. To obtain an accurate waveform of electrical signals in the THz region, we found it necessary to remove the longitudinal component of the electric field. The longitudinal component cannot be observed at the region of the slow tail of the transverse component. We concluded that the experimental and theoretical treatment which do not assume TEM mode approximation is essential for the complete understanding of the EO sampling signal of the THz frequency region.

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