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Performance of MBE Grown CdTe Photoconductor Arrays for Hard X-ray Detection.*

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PERFORMANCE OF MBE GROWN CdTe PHOTOCONDUCTOR ARRAYS
FOR HARD X-RAY DETECTION

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(ABSTRACT)

Photoconductor linear array detectors for hard x-ray photon detection were fabricated using Molecular Beam Epitaxially (MBE) grown (111)B CdTe layers on (100) orientation Si substrates. Since the Si substrates used for the MBE growth are semiconducting, the CdTe epitaxial layers were removed from the substrates using chemical etching of Si and mounted on insulating ceramic substrates. Linear array detectors were then fabricated on the resulting CdTe layers. The response current uniformity of 64 element photoconductor array was measured at 300 K and 230 K. The ohmic contact to the highly resistive CdTe is excellent to provide the linear response to the x-ray photon counts. The response current was linearly increased in the energies from 7 to 19 KeV. The stability of the detectors are very satisfactory and they were tested for over an extended period of time without any noticeable degradations. The performance of the photoconductor was greatly improved when the detector was cooled by a thermoelectric cooler. Due to its reduced noise at these temperatures, the dynamic range of the detector response increases to nearly four decades at 230 K.

1. INTRODUCTION

CdTe is a II-VI semiconductor material and was found to be useful for the detection of high energy radiations, such as x rays and gamma rays^(1,2,3,4,5,6). The high atomic number of Cd (48) and Te(52) and its high stopping power are the main advantage for the such radiation detector applications. The bandgap of CdTe is fairly large and the intrinsic carrier concentration is low. The high resistivity is very attractive for room temperature operations. Because of its large absorption coefficient, 10 - 20 μm thick CdTe layer should capture most x-ray photons in the interesting energy range for crystallography (8-20 keV). E. Rossa *et al.* and other groups attempted photoconductors made of thin polycrystalline CdTe grown by MOCVD^(7,8,9). However the use of polycrystalline crystals limits their applications because of the large photoconductor dark current.

We have utilized MBE grown single crystalline CdTe layers to develop linear photoconductor arrays for synchrotron radiation diagnosis^(10, 11,12,13). It is of a great advantage to use thin MBE grown layers in order to reduce the dark current and to achieve ultra fast temporal response. Since MBE epitaxial growth of MBE (111)B CdTe on (100) Si substrates was first reported⁽¹⁴⁾, significant improvements were accomplished so that Double Crystal Rocking Curve Full Width Half Maximum (DCRC FWHM) of as low as 60 arcs has been obtained⁽¹⁵⁾. Also MBE growth provides an excellent uniformities of both thickness and defect levels on large area⁽¹⁶⁾, which are the basic requirements to obtain uniform response of array devices as in most optical detectors.

2. FABRICATION

The undoped (111)B CdTe layers were grown directly on 3 inch (100) Si substrates by MBE using a proto-type OPUS 45 system. The details of the growth parameters and conditions are reported elsewhere^(16,17,18). The CdTe layer thickness varies between 10 to 20 μm and the crystalline

qualities of the layers determined by x-ray DCRC FWHM range from 200 to 500 arcsec. It should be mentioned that the CdTe used for the detectors reported in this paper are of relatively poor quality compared with those of recently grown MBE CdTe at the University of Illinois at Chicago. The resistivity of the underlying Si substrates is several orders of magnitude lower than that of the MBE grown CdTe. It is necessary to remove the epitaxial CdTe layers from Si and to mount on an insulating substrate. Otherwise the substrates would provide the conducting path for the generated carriers in the highly resistive CdTe. After a CdTe/Si layer was mounted on an insulating ceramic substrate using epoxy, the Si substrate was etched in 80% KOH in DI water at 80 °C, where the chemical etching of Si is significantly enhanced along the interface between CdTe and Si. Within 5 minutes, the Si substrate is removed from the CdTe layer on the ceramic substrate. As a result, the surface of the CdTe is the original interface with Si substrate, the crystalline quality of which is believed to be poor because of large lattice mismatch (19 %). Therefore top 2 μm of CdTe was chemically etched in 1% Br_2/HBr etchant. A conventional photolithography was used to fabricate linear photoconductor array devices. In order to avoid crosstalk, the CdTe between each photoconductor and its metal strip was completely etched away, followed by electroless Au metal deposition for ohmic contact to the high resistive CdTe. The test photoconductor gap varied from 20 to 50 μm with 50 μm width. The arrays are of 100 μm pitch size and consists of either 64 or 256 elements each.

3. RESULTS AND DISCUSSION

Current-voltage measurements were made on one of the test photoconductor arrays at various temperatures, the results of which are shown in Fig. 1. For the minority carrier generation, the detector was illuminated by an incandescent lamp, and the generated current increases by more

than an order of magnitude. As illustrated in the figure, the electroless deposited Au metal provides fairly good ohmic contact on the highly resistive MBE CdTe. From the current-voltage measurement at 300 K, we obtained the MBE CdTe resistivity of $8 \times 10^7 \Omega\text{-cm}$, assuming perfect insulation of the underlying epoxy. This is somewhat lower than that deduced from other MBE CdTe grown on lattice matched $\text{Hg}_{1-x}\text{Cd}_x\text{Te}^{(19)}$. This is because devices were made on the most defective region of the layer where electrically active defects such as dislocations or point defects, generated by the large lattice mismatch with Si, are still present in spite of removal of the top 2 μm thick layer. For this particular CdTe layer, the crystalline quality on the original front surface was as good as 220 arcsec DCRC FWHM, however when x-ray DCRC was measured on the back surface after 2 μm removal of the top layer, FWHM increased to 580 arcsec.

The current conduction observed in insulating CdTe follows Space-Charge-Limited(SCL) current^(19,20,21) or Frenkel-Poole mechanism⁽²²⁾. These processes are determined by a weak temperature dependence of the dark current. However neither form of conduction mechanism was found in our as-grown MBE CdTe photoconductor. It is observed that the dark current decreases exponentially as the temperature decreases from room temperature to 250 K, indicating that the current in this temperature range is due to ohmic conduction⁽²³⁾. The exponential decrease of the dark current is due to the free carriers generated from trap levels in the undoped MBE CdTe. We obtained an activation energy of 0.67 eV, which is believed to be related to electron trap levels in the as-grown MBE CdTe.

Response uniformity is a measure of importance of the array detector performance for imaging devices. For a linear 64 element photoconductor array, the uniformity of both dark and generated current was measured at various temperatures and the results are shown in Fig. 2. The photogeneration was obtained by shining yellow incandescent light on the photoconductors with

a photon flux of $4.5 \times 10^{16}/\text{sec-cm}^2$. It is noticed that as the dark current decreases with the temperature, the noise decreases by nearly the same orders of the magnitude. While the photogeneration currents seem to decrease by a small fraction. Since the generation current is due to the product of both lifetime and the mobility of the minority carriers, it shows very weak temperature dependence in the temperature range. Therefore overall signal to noise ratio is dominated by the decrease of the dark current.

MBE CdTe photoconductor response to 8 keV x-ray photons generated by a Cu rotating anode was measured and linear dependence to the photon counts was obtained as shown in Fig. 3. Since the detector sensitive area ($20 \times 50 \mu\text{m}$) is far smaller than the x-ray beam sizes ($200 \times 200 \mu\text{m}$), the counts of the x-ray photons impinging onto the detector sensitive area were deduced from other indirect measurements. The total x-ray photon counts were measured using an ionization chamber. Both direct and attenuated beam profiles were measured by scanning a single photoconductor. Then the measured beam profiles were normalized and compared with each others. They showed nearly consistent FWHM's of the response curves along x and y directions. At its minimum power of the rotating anode x-ray generator (20 KV acceleration voltage and 10 mA generation current), we obtained 1.1×10^3 counts/sec impinging onto the detector sensitive area of a photoconductor when it is placed in the center of the beam. The x-ray beam was attenuated by a number of aluminum foils and the photon counts were monitored by the ionization chamber. It was determined that the transmission of the x-ray is 65 % for a sheet of aluminum foil. The photoconductor was then placed in the center of the beam and the response was subsequently measured with the attenuations. Due to the reduced dark current at 230 K, the minimum detectable photon count was calculated to be 3.3 photons/sec-detector sensitive area. At room temperature, the response was measured with increased x-ray generation power of 45 KV and 160 mA. To the direct beam, the saturation of the preamplifier

output limited the photoconductor response. With the attenuations, linear decrease of the response is observed as shown in the figure. The minimum detectable photon count was calculated to be 55 photons/sec at room temperature.

Linear dependence of the response to x-ray photon energy was obtained at room temperature with synchrotron x-ray EXAFS beam line (NSLS/X18B). The x-ray energy was controlled by a double Si crystals and the photon counts were monitored using an ionization chamber filled with N_2 gas. In spite of relatively far more photons passing through the N_2 filled ionization chamber, the x-ray photon absorption in the ionization chamber slightly decreased in the energies higher than 16 keV, whereas MBE CdTe exhibited linear increase of the response in the energy up to 19 keV. This illustrates that the MBE CdTe layer effectively stops most photons of the energies. In the low energies less than 10 keV, the response slightly deviates from the linearity. This seems to be due to the photon absorption in the air.

4. CONCLUSION

The MBE grown CdTe of high qualities show high resistivity at room temperature, so they are readily suitable to x-ray or high energy radiation detector applications. It was also observed that excellent ohmic contact is formed on the CdTe by electroless deposited Au metal. The dependence of both temperature and bias verify that the current conduction mechanism is ohmic. Response uniformity was demonstrated for a 64 element linear array detector at various temperature. The dark current changes by nearly 3 orders of magnitude from room temperature to 200 K. An exponential decrease of the dark current greatly decreases the noise current by the same orders of the magnitude, thus substantially increasing the signal-to-noise ratio and improving the detector performance. The minimum detectable photon counts was measured with 8 keV x-ray energy. We obtained minimum

detectable photon counts of 55 and 3.3 photons/sec impinging onto the detector area, at 300 K and 230 K, respectively. Finally, linear dependence of the photoconductor to x-ray energies of 8 to 19 KeV was presented. This illustrates that the MBE CdTe of 15 μm thickness is thick enough to virtually absorb most of the x-ray photons of 8 to 19 KeV energies. These results indicate that MBE grown CdTe is one of the most suitable detector materials to meet the requirements of future synchrotron applications.

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FIGURE CAPTIONS

1. Current-voltage measurements at various temperatures. It is noticed that the currents are linearly dependent on the bias. As the temperature decreases, the dark current decreases exponentially from room temperature to 240 K with an activation energy of 0.67 eV. This illustrates that the current conduction is ohmic.

2. Response uniformity of 64 element photoconductor array. For generation current, the array photoconductor was exposed to a yellow light with a flux of 4.5×10^{16} photons/cm²-sec. It is noticed that as the dark current decreases with temperature, the noise decreases with the same order of magnitudes. At 200 K, the noise is limited by the circuitry used for this measurements.

3. Dynamic range of the photoconductor response to 8 keV x-ray photons at 300 K and 230 K. At the minimum generation power of the rotating anode generator, photon count of the direct beam was determined by an ionization chamber and found to be 1123 photons/sec impinging onto the detector sensitive area. The minimum detectable photon counts onto the detector area were measured to be 55 and 3.3 photons/sec-detector area at 300 K and 230 K, respectively.

4. Energy dependence was measured with synchrotron x-ray (NSLS/X18B) at room temperature. This linear dependence indicates that most of x-ray photons in the energies are effectively stopped within the MBE CdTe layer, contributing the response signal.

Linear Energy Dependence

Dynamic Response Range

Response Uniformity

Current-Voltage Characteristics