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Optical Properties of CdTe-PbTe Multilayer Heteroepitaxial Structures Prepared by ICB Technique

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The CdTe-PbTe multilayer heteroepitaxial structures have been prepared by the ionized cluster beam (ICB) technique, and the crystal and optical properties of the structures are investigated. The formation of the multilayer structures is confirmed by Rutherford backscattering measurement, and the optical absorption measurement is found to indicate the existence of the n=1 miniband in the potential well of CdTe-PbTe superlattices. The ICB technique has an advantage of low substrate temperature growth, and it is found to have a high potential for preparing functional thin films.

I. Introduction

Recent interest in the multilayer structures has directed to the realization of functional devices.[1-3] As the constituent layers of the periodic structures, CdTe and PbTe films are employed, for which the lattice constant and the energy gap are respectively 6.478 and 6.46 Å and 1.5 amd 0.32 eV at 300K. Since the lattice misfit of these materials is within 0.3%, heteroepitaxial structures with few structure defects can be expected to be produced. In a CdTe-PbTe multilayer structure, CdTe has a large band gap and is suitable for potential barrier of electron or hole carriers. Also, PbTe has a large dielectric constant of a few hundreds and is an attractive material for preparing optoelectronic devices.

The ionized cluster beam (ICB) technique,[4-6] in which one cluster consists of 500-2000 atoms loosely coupled together, has an advantage of low substrate temperature growth with the aids of the ionic charge and the kinetic energy of ions. The presence of ions and the kinetic energy of ions in the cluster beams influence the film characteristics.[7] For example, the CdTe films prepared using the ionized clusters showed the improvement of crystallinity and surface flatness as comparison with films obtained using neutral clusters.[8]

In this paper, the CdTe-PbTe multilayer structures with each ultrathin layer are prepared by the ICB technique, and the crystal and optical properties of the structures are investigated.

II. Experimental Procedures

2.1 General aspect of ICB system

Figure 1 shows the schematic diagram of the ICB deposition system, in which two ion sources are assembled to cross the cluster beams on the substrate surface. Source materials are charged in carbon crucibles separately, and they are heated by direct heating. The clusters are formed by adiabatic expansion of the vapourized material, when ejecting into a high vacuum region through the nozzle of crucible. They consist of about 500-2000 individual atoms loosely coupled together. Some of clusters are ionized by electron bombardment and the ratio of ionized clusters to total clusters can be controlled by changing the electron current (Ie) for ionization, e.g., 10 to 40 percent of clusters are ionized under the conditions of Ie = 100 - 300 mA.[9] Each ionized cluster is assumed to have a single charge, and

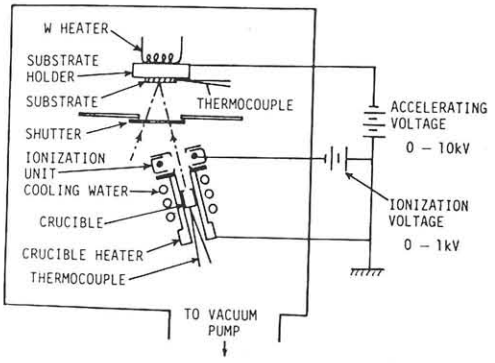

Fig.1 Schematic diagram of the ICB deposition system (two crucible method).

thus it has a small charge to mass ratio enabling a film deposition on an insulating substrate without the trouble of charging up. Ionized clusters can be accelerated by the acceleration voltage (Va). With increasing the acceleration voltage, the migration of adatoms on the substrate surface is enhanced even at comparatively low substrate temperature, which is one of the remarkable features in the ICB technique. Even without acceleration of the ionized clusters, the presence of the ionized particles in the source materials greatly influences the film formation activity and the chemical reaction activity, although absolute amount of charge is quite few.

2.2 Preparation conditions

CdTe and PbTe ingots were used as source materials, and the crucibles for CdTe and PbTe were heated up to 700 and 750°C, respectively. The CdTe and PbTe clusters which were formed when ejecting through a nozzle of the crucible, were ionized and accelerated toward a substrate. The electron current (Ie) for ionization and the acceleration voltage (Va) were adjusted at Ie = 200 mA and Va = 5 kV. The substrate temperature (Ts) was kept at Ts = 250°C. The background pressure was 2×10^{-6} Torr. The substrate used was Si (111) and InSb(111)B. Si substrates were chemically cleaned using acetone, trichloroethlene, hydrofluoric acid and deionized water. For InSb substrates, chemical cleaning was made by acetone and deionized water in addition to the etchant of nitric, hydrofluoric and acetic acids. Prior to deposition, the InSb substrate was preheated at 450°C for 1 hour. Deposition time for each layer of CdTe and PbTe was adjusted by a mechanical shutter control.

III. Experimental Results and Discussions

Figure 2 shows Rutherford backscattering spectrum for 5 periods of CdTe-PbTe multilayer structure formed on a Si substrate with each layer thickness of 400 Å. The energy width of bottom for each periodic peak is in good agreement with the estimate based on the semiempirical energy-loss values corresponding to the sum of layer thickness, i.e., 800 Å. The oscillatory nature of the backscattering yield in the figure can be explained by the overlapping of yields from Cd and

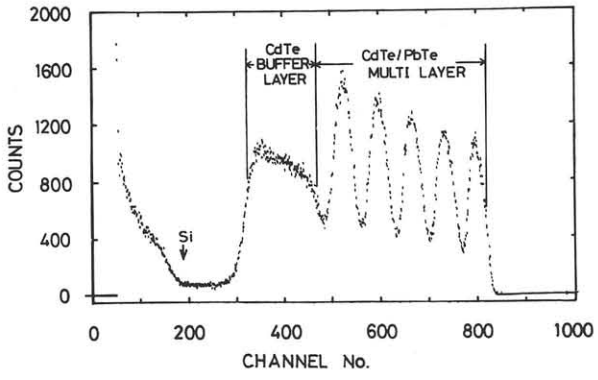

Fig.2 Backscattering spectrum along random directions of a CdTe-PbTe multilayer structure.

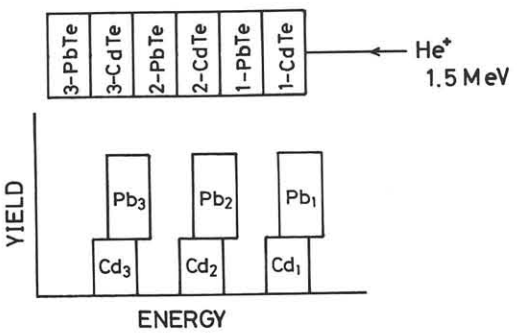

Fig.3 Schematic representation of the origin of the oscillatory backscattering yield.

Pb elements in each layer as shown in Fig.3. The energy width of the schematic spectrum Cd_1 is proportional to the thickness of the first CdTe layer, and the total energy loss of the projectile in its inward path and its outgoing path through the 400 Å layer of CdTe gives some energy shift from that scattered from Cd_1 at the surface. Also, the backscattering yield from the Pb_1 at the top interface is displaced by some energy from the same depth. This makes the Pb_1 signal overlap with the Cd_1 signal. Thus the backscattering yields from Cd and Pb elements in each layer were overlapped, resulting in the appearance of 5 peaks and valleys in the backscattering spectrum of Fig.2.

In order to study the optical property of a CdTe-PbTe multilayer structure on a Si substrate, the reflectance and transmittance in the infrared wavelength region were measured. Figure 4 shows the optical absorption spectra for the CdTe-PbTe structure with 60 periods, in which each layer is 65 and 80 Å thick. The arrows show the boundary of the absorption corresponding to the n=1 miniband. With decrease of layer thickness, the energy corresponding to the miniband shifts to the

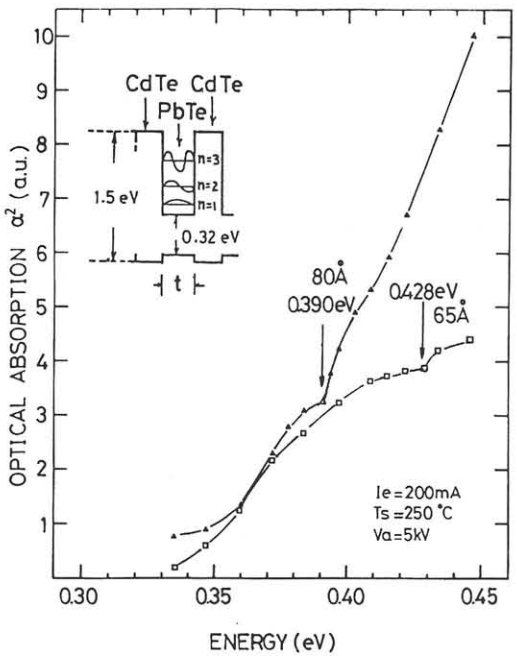

Fig.4 Optical absorption spectra for CdTe-PbTe multilayer structures with 60 periods of different layer thickness (t): t = 80 and 65 Å.

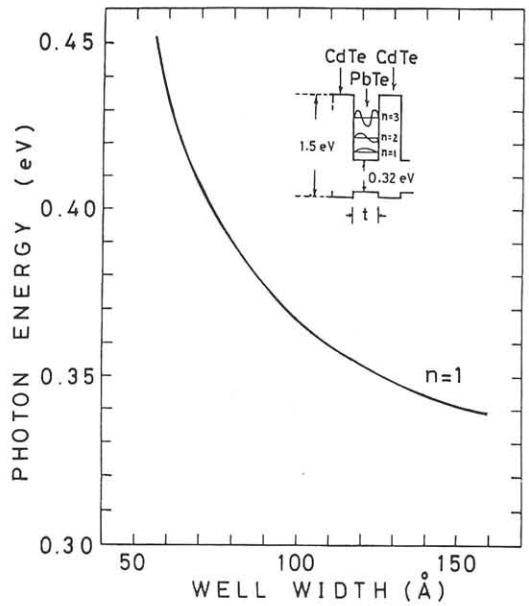

Fig.5 Allowed energy of n=1 miniband calculated as a function of well (or barrier) width for CdTe-PbTe multilayer structure.

higher energy level. The value of the position of the n=1 miniband can be calculated using the following expression based on the Kronig-Penney band model.[10,11]

$$\left|\cosh(\alpha a)\cdot\cos(\beta b) + \frac{\alpha^2-\beta^2}{2\alpha\beta}\cdot\sinh(\alpha a)\cdot\sin(\beta b)\right| \leq 1 , \quad (1)$$

$$\alpha = 2 m_1 (V - E)^{1/2} / \hbar , \quad (2)$$

$$\beta = (2 m_2 E)^{1/2} / \hbar , \quad (3)$$

where E is the electron or hole energy in the direction perpendicular to the surface, V, the barrier height, a, the barrier width, b, the well width, and m_1 , m_2 , the effective masses. Figure 5 shows the value of the allowed miniband (n=1) calculated with the assumption of being equal for the barrier and well widths (a = b). The values corresponding to the miniband obtained in the optical absorption measurement agree with the calculated value, and the multilayer periodic structures were found to be synthesized from ultrathin layers such that quantum effects are exhibited.

In the CdTe-PbTe multilayer structures, CdTe with a thickness of 1500 Å was grown as a buffer layer before forming the multilayer structures. The crystallinity of the CdTe buffer layer on a Si (111) substrate was improved with increase of acceleration voltage. In a case of CdTe buffer layer on an InSb(111)B substrate with a small misfit of 0.03%, the crystallinity was good with the aids of the kinetic energy of ions and the ionic charge. Figure 6(a) shows the RHEED pattern for CdTe film grown as the buffer layer on an InSb substrate. The pattern was streaking and the surface was found to be flat and smooth. For the CdTe-PbTe multilayer structure with 20 periods of layers on an InSb substrate, in which each layer was 150 Å thick, RHEED pattern for the top layer of CdTe was good as shown in Fig. 6(b). As comparison with that for the CdTe buffer layer, the crystallinity remains good, although the surface

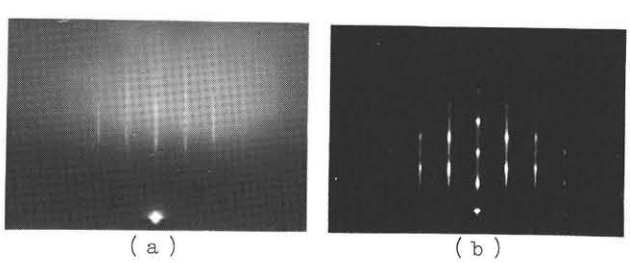

Fig.6 RHEED patterns for (a) the CdTe buffer layer and (b) the top layer of CdTe in the multilayer structure.

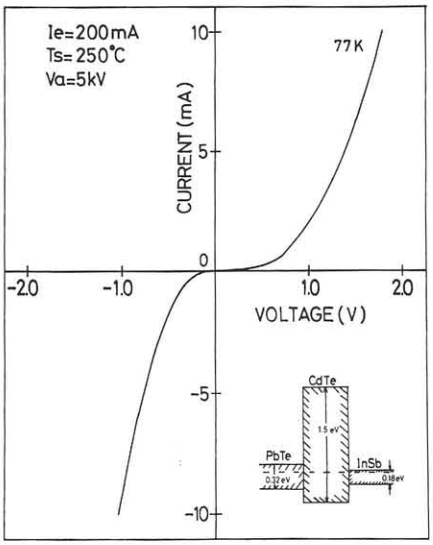

Fig.7 Current - voltage characteristic measured at 77 K for the multi-heterojunctions of PbTe-CdTe-InSb.

is a little rough. It should be noted that the RHEED patterns were not the in-situ observation and that they were observed for the samples after taking out of the growth chamber.

Figure 7 shows the current-voltage (I-V) characteristic for PbTe-CdTe-InSb heterostructures measured at 77 K. The sample was prepared by depositing PbTe film on CdTe buffer layer formed on an InSb substrate. The thickness of both PbTe and CdTe films was 1500 Å. The polarity of the current was determined to choose an InSb substrate as a reference. The ohmic contact for the sample was Au (gold) on PbTe layer and solder on InSb substrate, respectively. As shown in the figure, the I-V characteristic exhibits the nonlinearity in both forward and reverse directions, and it was found that the band gaps of PbTe (0.32 eV) and InSb (0.18 eV) are within that of CdTe (1.5 eV).

IV. Conclusions

The CdTe-PbTe multilayer heteroepitaxial structures were prepared by the ICB technique, and the crystal and optical properties of the structures were investigated. From the optical absorption spectrum, it was found that the n=1 miniband was present in the potential well of one-dimensional periodic potentials, and that the position was shifted to higher energy level with decrease of layer thickness. The energy level was found to agree well with the theoretical value calculated by the Kronig-Penney band model. The current-voltage (I-V) characteristic was measured for PbTe-CdTe-InSb multi-heterostructures, and it was found from the nonlinear characteristic that the band gaps of PbTe (0.32 eV) and InSb (0.18 eV) were within that of CdTe (1.5 eV). From these results, the CdTe-PbTe multi-heterostructures are expected for applying to new types of optoelectronic devices, and it can be found that the ICB technique has a high potential for preparing functional thin films with ultrathin and multilayer structures.

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