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Amorphous-Se/GaAs—A Novel Heterostructure for Solid State Devices—

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Interface properties of an amorphous-Se/GaAs heterostructure made on a Se-stabilized (2x1) GaAs(001) surface are investigated using photoemission spectroscopy and electrical measurements. The band alignment of the a-Se/GaAs is found to be a staggered one with the valence band discontinuity of -0.27 ±0.05 eV. This is suitable for a possible application of this novel heterostructure, in which photogenerated holes in GaAs are injected to a-Se for avalanche multiplication.

Introduction

It has previously been suggested that an interface free of midgap pinning levels can be realized in the heterostructure composed of amorphous Se and single crystal GaAs.[1] Amorphous (a-) Se is a semiconductor with a bandgap of 2.1 eV. A-Se has photoconductivity and has been utilized as a target material of image pick-up tubes. Furthermore, the ratio of hole to electron ionization rates is more than an order of magnitude larger for a-Se than for III-V.[2] Highly sensitive avalanche multiplication is thus possible in a-Se. The III-V semiconductors, on the other hand, have many excellent properties such as tunability of band gap. The presence of semiconductors with totally different properties makes the a-Se/III-V semiconductor heterostructure extremely interesting for device application. In the present study, properties of a-Se/GaAs interface are investigated using photoemission spectroscopy and electrical measurements to explore the possibilities of this novel heterostructure for solid state devices. The interface chemistry and the band bending in a-Se/GaAs are examined by photoemission spectroscopy. The valence band discontinuity, which plays a leading role in determining the transport across the interface, is also determined. Application to photoelectric and imaging devices is proposed based on the band alignment found in this study.

Experimental procedures

The a-Se/GaAs structure was fabricated as follows. An epitaxial GaAs layer was grown on (001) GaAs wafer by MBE. The sample was then transferred to anther connected chamber equipped with a Se effusion cell. In this chamber, the sample was exposed to a Se flux with the intensity of 1×10^{-6} Torr at 400°C. This gives rise to the formation of a Se-stabilized (2x1) surface. An a-Se film was then deposited on the (2x1) surface at room temperature. Surface-sensitive photoemission spectroscopy analysis of the a-Se/GaAs was done ex-situ at the branch line 8A of the Photon Factory in the National Laboratory of of High Energy Physics, Japan. Exposure of the sample to atmosphere for transfer was made less than 1 hour to avoid significant oxidation of the a-Se surface.

The transport property across the interface was examined with a-Se/GaAs diodes having 500µm-diameter gold electrodes on the a-Se and back ohmic contacts.

Results and discussion

The top spectra in Fig. 1 shows the As and Ga 3d core level peaks for the a-Se/GaAs(001). The thickness of the a-Se film is about 10 Å. The bottom spectra are for the Se-stabilized (2x1) surface obtained by heating to 300°C, at which the top Se film is evaporated off the surface. The binding energy is referenced to the Fermi level as measured from a freshly evaporated gold film. The substrate and epitaxial GaAs layer are both n-type. The Ga 3d/As 3d intensity ratio is found to be 3.12 for the surface with the overlayer, which is larger than the value, 2.66, for the (2x1) surface. This indicates the occurrence of Ga-outdiffusion at the a-Se/GaAs interface.

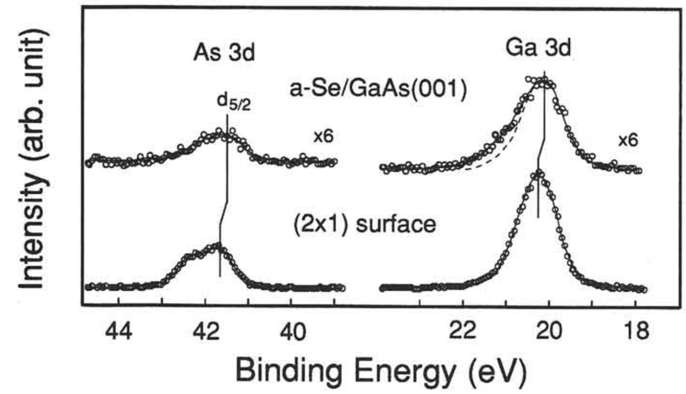

Fig. 1 As and Ga 3d photoelectron spectra of a-Se/GaAs(001) and Se-stabilized (2x1) GaAs(001) surface. The excitation photon energy is 125 eV.

The increase in the intensity ratio is attributed to the additional emission in the higher binding energy side of the Ga 3d peak. The chemical shift of this additional tail from the main peak is estimated to be about 1 eV. This tailing is probably due to the emission from Ga atoms diffused toward the a-Se surface and oxidized during the exposure to atmosphere for sample transfer. The As 3d peak, on the other hand, is not significantly affected by the presence of the a-Se overlayer, although a slight broadening is observed compared with the peak for the (2x1) surface, which shows only single spin-orbit doublet. This is in contrast with Ge/GaAs system[3], in which considerable As-outdiffusion is observed. The Se-stabilized (2x1) surface is covered with an epitaxial $GaSe_x$ layer few-monolayers thick.[1] This surface layer probably inhibits the As-outdiffution at the a-Se/GaAs junction leading to a fairly abrupt interface, except for the small amount of the Ga-outdiffusion.

As seen in Fig. 1, both As 3d and Ga 3d peaks for the a-Se/GaAs(001) are shifted toward higher binding energy than for the (2x1) surface. The shift is found to be 0.2 eV. The Fermi level position for the (2x1) surface is 1.32 to 1.42 eV from the top of GaAs valence band as determined from the observation of valence band edge and As 3d band bending shift. The Fermi level position at the a-Se/GaAs interface is thus estimated to be 1.1 eV above the GaAs valence band maximum. This suggests the presence of pinning levels at 0.3 eV below the conduction band minimum. This is in agreement with the a-Se/GaAs MIS diode capacitance-voltage(C-V) characteristics,[1] which clearly indicates the presence of high density interface levels around 0.3 eV below the conduction band minimum. The band is nearly-flat at the (2x1) surface, indicating the absence of these pinning states at the (2x1) surface. The pinning states present at the a-Se/GaAs interface are thus created through the interface formation, and may be attributed to some structural defects in the a-Se film. We return to this point later.

Figure 2 shows typical valence band edge and As 3d spectra of the a-Se/GaAs(100) and a clean GaAs surface. The clean surface is obtained by heating the sample up to 600°C, at which the surface Se atoms are completely desorbed from the surface. The shift observed in the As 3d peak is a band-bending shift. The valence band discontinuity at a-Se/GaAs interface is estimated from the difference of the energy position of the valence band edge measured with respect to the bulk As 3d peak, thereby eliminating the contribution of band-bending shift. Figure 3 shows the valence band discontinuity (ΔE_v) measured for a few samples. The valence band discontinuity at a-Se/GaAs interface is

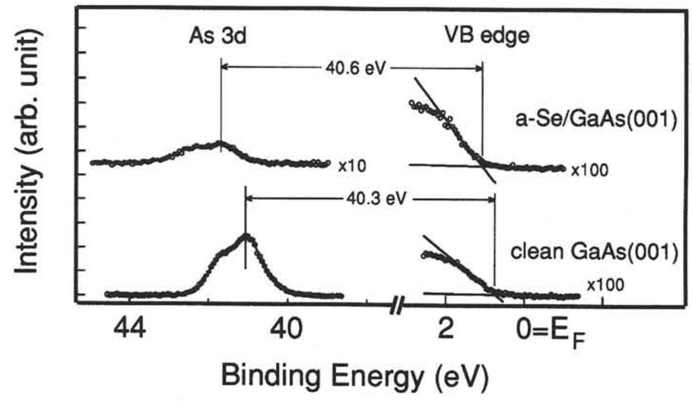

Fig. 2 Valence band edge spectra of an a-Se overlayer on GaAs(001) and a clean clean GaAs(001) surface. The excitation photon energy is 100 eV. The valence band maximum is measured with respect to the bulk As 3d peak. The difference for the two surfaces gives the valence band discontinuity at the a-Se/GaAs interface.

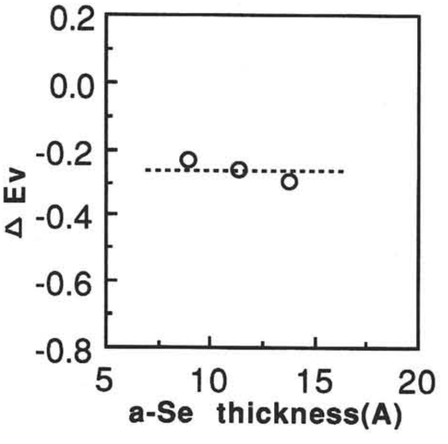

Fig. 3 Valence band discontinuity measured through photoemission spectroscopy analysis. The a-Se thickness was estimated from the attenuation of the As 3d peak intensity assuming the photoelectron escape depth of 5.5 Å.

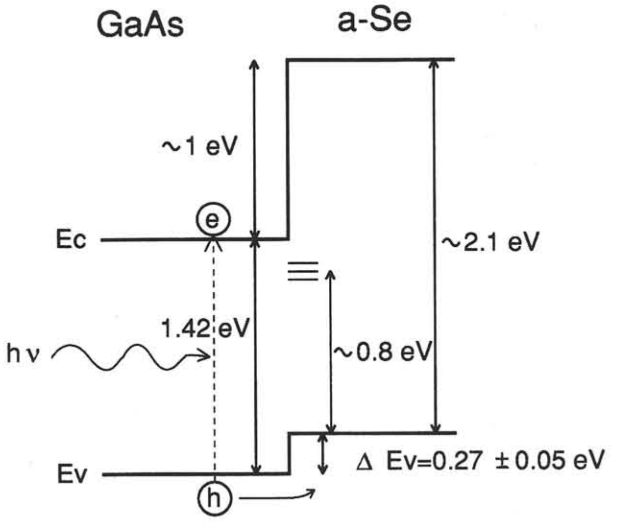

Fig. 4 The band alignment of a-Se/GaAs determined from the photoemission spectroscopy analysis. Note that there is no barrier for injection of holes from GaAs to a-Se. Pinning states are present at 0.8 eV above the a-Se valence band maximum (see text for more detail).

determined as -0.27 ±0.05 eV. The negative sign indicates that the band alignment is a staggered one. Figure 4 shows the band diagram found in this study for the a-Se/GaAs heterostructure. Note that there is no barrier for injection of holes from GaAs to a-Se.

Also indicated in Fig. 4 is the energy position of the pinning states at the a-Se/GaAs interface found from the photoemission spectroscopy analysis and the diode C-V characteristics. Their position appears to be about 0.8 eV above the a-Se valence band maximum. This energy position coincides with that of the reported bulk deep levels in a-Se.[4] This suggests that the pinning states observed in the a-Se/GaAs are associated with some defects near the interface in the a-Se film.

The photoemission results are further confirmed in a-Se/GaAs diode current-voltage (I-V) characteristics. The structure and the I-V characteristics of the diodes are shown in Fig. 5. The diode made on a p-type substrate shows a Schottky-like current onset in the forward bias, while the forward current as well as reverse current are small for the diode made on a n-type substrate. These are the expected behaviors for the band alignment shown in Fig. 4.

The present results suggest that a-Se/III-V semiconductor heterostructures can be utilized as a SAM (Separated Absorption and Multiplication) structure. Photogenerated holes in the III-V semiconductor region can be injected efficiently to the a-Se region since there is no potential barrier at the junction (see Fig. 4). The holes are then multiplied in the a-Se through avalanche process. The a-Se/III-V heterostructures, in which the band gap of the III-V semiconductor is tunable, provide a possibility of realizing highly-sensitive imaging devices and photodetectors operating at various wave lengths.

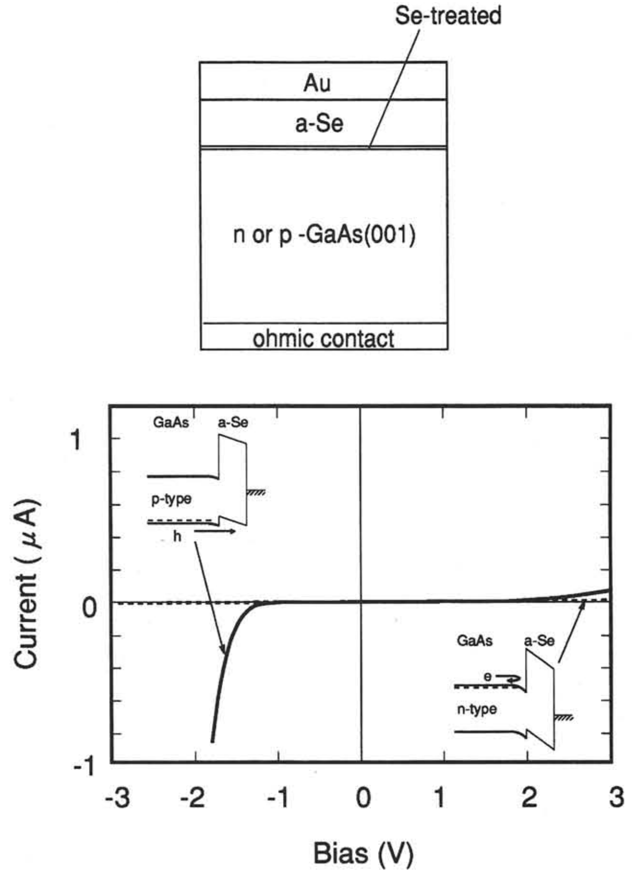

Fig. 5 Structure and current-voltage characteristics of a-Se/GaAs diodes. The solid and dashed lines are for the diode made on p-type and n-type substrates, respectively. The thickness of a-Se is about 1000 Å.

Acknowledgments

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