Photoelectric conversion characteristics of c-Se-based thin-film photodiodes in imaging device

S Imura¹,², K Kikuchi¹, K Miyakawa¹, H Ohtake¹ and M. Kubota¹

¹NHK Science and Technology Research Laboratories, Kinuta, Setagaya-ku, Tokyo 157-8510, Japan

E-mail: imura.s-la@nhk.or.jp

Abstract. Herein, we report the use of high-efficiency crystalline-selenium-based (c-Se-based) thin-film heterojunction photodiodes in imaging devices. As a novel experiment, we use an image pickup tube with a photoelectric conversion layer consisting of n-gallium oxide (Ga₂O₃)/p-c-Se heterojunction photodiodes to obtain high-resolution images at a relatively low applied voltage. We reduce the thickness of the Ga₂O₃ layer to expand the depletion layer into the c-Se layer at a lower applied voltage. In addition, Sn-doping of the Ga₂O₃ layer effectively increases the carrier concentration, thereby allowing the photodiode to operate at a lower voltage.

1. Introduction

Recently, the development of high-resolution high-speed complementary metal-oxide semiconductor-based (CMOS-based) image sensors has rapidly increased the demand for highly sensitive visible-light photodetectors. Satisfying this demand requires a significant enhancement of the sensitivity of photodetectors beyond what is possible with conventional silicon-based photodiodes. Motivated by this demand, we are developing a CMOS image sensor overlaid with a photoelectric conversion layer, which would allow satisfying the various requirements of high sensitivity, low crosstalk, high dynamic range, and so on.

Because of the excellent spectral response of crystalline-selenium-based (c-Se-based) photodiodes over almost the entire visible spectrum, they are promising candidates for fabricating highly sensitive visible-light photodetectors. In addition, because of the low crystallization temperature of selenium [1], all fabrication processes may be done below 200°C, which is advantageous for CMOS manufacturing.

In this study, n-Ga₂O₃/p-c-Se heterojunction photodiodes are used to demonstrate the possibility of high-efficiency visible-light photodetectors operating at a low applied voltage. Furthermore, in a novel experiment using a pickup tube with a photosensitive layer consisting of Ga₂O₃/c-Se photodiodes, we obtain high-resolution images at a relatively low voltage.

2. Experimental procedure

Figures 1(a) and 1(b) show the cross section of a pickup-tube structure and a cell structure, respectively. For the pickup tube, an n-type hole barrier was made by depositing 20-nm-thick Ga₂O₃ films over indium-tin-oxide (ITO) films on glass substrates by room-temperature radio-frequency
magnetron sputtering. Next, sub-nanometer-thick tellurium (Te) films and 500-nm-thick a-Se films were successively deposited by room-temperature vacuum evaporation. The amorphous selenium (a-Se) was completely converted to c-Se by annealing at 200°C. Finally, beam-landing layers made of 10-nm-thick di-antimony tri-sulfide (Sb$_2$S$_3$) porous films deposited by vacuum evaporation served to prevent the secondary-electron emission.

The cells had the same structure and materials as the pickup tubes except that the di-antimony tri-sulfide films were replaced by 30-nm-thick ITO films deposited by direct-current magnetron sputtering to serve as transparent top electrodes.

**Figure 1.** Cross-sectional schematic of (a) pickup tube structure and (b) cell structure.

3. Results and Discussion

3.1. Imaging experiment with pickup tube

**Figure 2.** Images from pickup tube incorporating (a) Ga$_2$O$_3$/c-Se pn photodiode and (b) ITO/c-Se Schottky photodiode at an applied voltage of 30 V.

Figures 2(a) and 2(b) compare an image acquired with a pickup tube containing Ga$_2$O$_3$/c-Se pn photodiodes and that containing ITO/c-Se Schottky photodiodes, respectively. This comparison clearly shows that a lower dark current and a higher resolution results from using Ga$_2$O$_3$/c-Se pn photodiodes rather than ITO/c-Se Schottky photodiodes. To obtain a resolved image with the pickup tube, the applied voltage must be increased to spread the depletion layer from the Ga$_2$O$_3$/c-Se interface into the c-Se layer, which is scanned by the electron beam. However, when using Schottky photodiodes, the potential barrier between ITO and c-Se is too low to prevent carriers from being injected into the c-Se from the ITO. At high electric fields, these carriers are the main contributors for the dark current. As a result, the image of Figure 2(b) is not clearly resolved. In contrast, when using Ga$_2$O$_3$/c-Se pn photodiodes, the potential barrier between ITO and Ga$_2$O$_3$ is extremely high because of the large band gap of Ga$_2$O$_3$ (4.9 eV) [2], leading to low dark current at high electric fields.
However, these devices still require a relatively high operation voltage (~30 V). In the next section, we discuss how to reduce this voltage to a level acceptable for CMOS circuits.

3.2. Influence of thickness and carrier concentration on operating voltage

We prepared the cell structures consisting of Ga\textsubscript{2}O\textsubscript{3} layers with varying thickness (5, 10, and 20 nm) and Sn concentration (0, 5, and 5.6 mol\%) to study how the thickness and carrier concentration of the Ga\textsubscript{2}O\textsubscript{3} layer affects the threshold voltage for saturation [see Figure 1(b)]. Figures 3(a) and 3(b) show the current–voltage (I–V) characteristics of an illuminated Ga\textsubscript{2}O\textsubscript{3}/c-Se heterojunction photodiode. The results show that the threshold voltage for saturation decreases with decreasing thickness of the Ga\textsubscript{2}O\textsubscript{3} layer and with increasing Sn concentration in the Ga\textsubscript{2}O\textsubscript{3} layer. Because of the low carrier concentration in the Ga\textsubscript{2}O\textsubscript{3} layer, the depletion layer mainly spreads through the Ga\textsubscript{2}O\textsubscript{3} layer at a lower voltage. Decreasing the thickness of the Ga\textsubscript{2}O\textsubscript{3} layer and increasing the Sn concentration leads to an increased carrier concentration in this layer [3], thus requiring a smaller applied voltage to spread the depletion layer into the c-Se layer.

**Figure 3.** Photocurrent as a function of applied voltage for (a) Ga\textsubscript{2}O\textsubscript{3}/c-Se photodiode with varying Ga\textsubscript{2}O\textsubscript{3}-layer thickness (5, 10, and 20 nm) and (b) Sn-doped Ga\textsubscript{2}O\textsubscript{3}/c-Se photodiode with different Sn-doping concentrations (0, 5, and 5.6 mol\%).

4. Conclusion

We report high-efficiency c-Se-based heterojunction photodiodes. By using a pickup tube with a photosensitive layer consisting of n-Ga\textsubscript{2}O\textsubscript{3}/p-c-Se heterojunction photodiodes, we obtained novel high-resolution images for such a technique. In addition, by decreasing the thickness of the Ga\textsubscript{2}O\textsubscript{3} layer and increasing the Sn concentration, we made photodetectors that operate at lower voltages, which is advantageous for CMOS-based solid-state imaging devices.

References

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