Paper

Evaluation of Potential Distribution in Channel Region of Amorphous InGaZnO Thin Film Transistor by Bias Applied Hard X-ray Photoelectron Spectroscopy

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The potential distribution image in the channel plane of an amorphous $InGaZnO_4$ (a-IGZO) thin film transistor in the device operation was evaluated by bias applied hard X-ray photoelectron spectroscopy (HAXPES). We observed that the potential in the direction of channel length changed as a function of source-drain and/or gate voltage condition. In particular, in the case of the turn-on voltage condition (saturation regime), a high potential region in the a-IGZO channel was clearly observed. HAXPES under bias voltage was found to be very useful to evaluate the potential in the channel region during transistor operation.

1. Introduction

For various transistor devices (such as Si, a wide band gap semiconductor, an amorphous oxide semiconductor, and an organic semiconductor), the potential distribution in the semiconductor channel region during the device operation needs to be evaluated to understand the device principle and further improve device performance. So far, scanning Kelvin probe force microscopy (KFM) and bias applied soft-X-ray photoelectron spectroscopy (PES) have been successfully used to investigate the spatial surface potential distribution of various semiconductor devices [1-3]. However, many semiconductor device structures have an altered surface layer and the charge transport occurs at a buried semiconductor and insulator interface, but these techniques do not enable us to detect the buried interface of the devices or the potential distribution in the depth direction without being affected by the altered surface layer.

Bias applied hard x-ray photoelectron spectroscopy (HAXPES) has been developed to evaluate the energy distribution of interface states and observe the electric potential in the semiconductor channel during the device operation [4,5]. Here, note that HAXPES can non-destructively probe the electronic states of the bulk and buried interface lying at depths of several tens of nm due to its large probing depth [6,7]. Therefore, bias applied HAXPES can be used to evaluate the potential distribution of the bulk region in the planer direction by eliminating the effect of the altered surface layer.
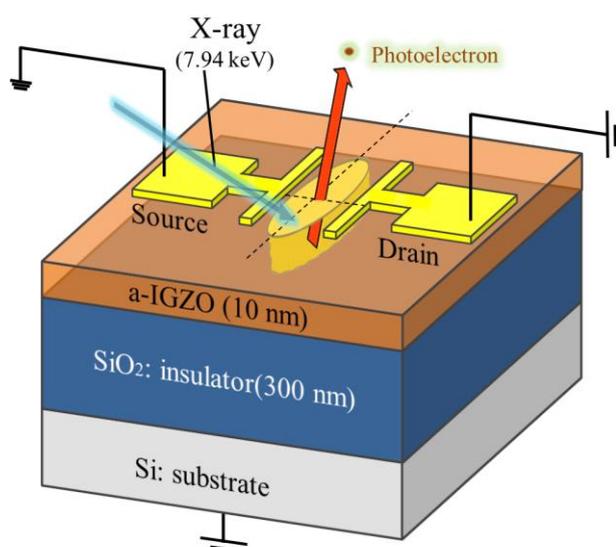
In the present study, we developed a bias applied HAXPES to evaluate the potential distribution image in the channel plane of an amorphous $InGaZnO_4$ (a-IGZO) thin film transistor (TFT). Note that, a-IGZO is attracting considerable attention because it is expected to be used as a high-performance channel material in TFTs for display applications [8,9]. However, a few studies have reported on the potential distribution of the amorphous oxide semiconductor transistor in device operation, but no studies have reported that of a spectroscopic technique. Therefore, in this study, we focused on the potential distribution of a-IGZO TFT.

2. Experimental

HAXPES measurement was performed at BL46XU in SPring-8. An incident X-ray with a photon energy of 7.94 keV, which was monochromatized with a Si(111)

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double crystal and Si(444) channel-cut monochromators, was horizontally and vertically focused on a sample surface by Rh-coated mirrors. Photoelectron spectra were observed by an electron spectrometer (VG-Scienta R-4000-10keV). The aperture of the analyzer slit was 0.5 mm with a curved rectangular shape, and pass energy was fixed as 200 eV. A total energy resolution of 230 meV was determined by observing the Au Fermi edge. To evaluate the potential distribution in the device operation, the source-drain voltage (V_{ds}) was maintained at 10 V with the source electrode connected to the ground, and the intended gate voltage (V_g) was applied throughout the HAXPES measurement. These electrodes were biased by the Keithley 2400 SourceMeter. Also, drain current was measured simultaneously. The measurements were carried out at room temperature.

An a-IGZO TFT with a bottom gate structure was used in the present study. A highly doped p-type crystalline Si wafer with a thermally grown 300-nm-thick SiO_2 layer was used as the gate electrode and the gate insulator. A 10-nm-thick a-IGZO film was deposited by RF sputtering using an $InGaZnO_4$ target. The process pressure of a mixed Ar and O_2 gas was 5 mTorr. The specimen was annealed at 350°C for 1 h in air. The Au source and drain electrodes were then vacuum-deposited at room temperature by shadow-mask. The channel length (L) and width (W) were 0.5 and 5 mm, respectively. Figure 1 schematically illustrates an a-IGZO TFT with a bottom gate
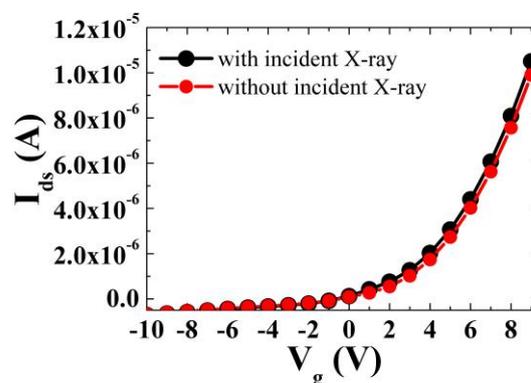
structure. X-ray was incident on five points in the direction of the channel length at the incident angle of 10°, and the emitted photoelectrons were detected at the take-off angle of 80°. These angles are defined as the angles between the paths of detected photoelectrons and the sample surface. The Ga $2p_{3/2}$ peaks with the highest intensity in the core levels of the IGZO channel were measured.   The beam size at the sample position was ~3.3 mm (in the direction of channel width) × ~0.02 mm (in the direction of channel length). Each analysis point was divided into 14 slices (spectra) in the direction of channel width.

3. Results and discussion

First, we examined the effect of the X-ray irradiation on the transfer curve results. Figure 2 shows the transfer curves of the a-IGZO TFT with and without X-ray irradiation (photon energy of 7.94 keV). As shown in the figure, the a-IGZO TFT shows good turn-on behavior, and almost the same transfer curves were obtained with and without X-ray irradiation. The saturation mobility (μ_{SAT}) was extracted from $I_{ds} = \mu_{SAT}(WC_{OX}/2L)(V_g - V_{th})^2$, where I_{ds} is the drain–source current and C_{OX} is the gate insulator capacitance per unit area. μ_{SAT} were found to be 2.1 and 2.3 cm^2/Vs with and without X-ray irradiation, respectively. An X-ray with the photon energy of 7.94 keV, which was used for HAXPES measurements, was found to barely affect the transfer curve characteristics.

Figure 3 (a) shows Ga $2p_{3/2}$ montage spectra at the center of channel length without the bias voltage ($V_{ds} = 0$ V and $V_g = 0$ V). As shown in this figure, the peak posi-

Fig. 1. (color online) Schematic illustration of a-IGZO TFT with bottom gate structure used for bias applied HAXPES measurements.


Fig. 2. (color online) Transfer curves of a-IGZO TFT at V_{ds} =10 V with and without incident X-ray with photon energy of 7.94 keV.

tions of Ga $2p_{3/2}$ spectra barely varied as a function of position along channel width. The main peaks located around a binding energy of 1118.4 eV are assigned to Ga-O bonds [10]. Figure 3(b) and 3(c) show Ga $2p_{3/2}$ montage spectra with the bias voltage of $V_{ds} = 10$ V and $V_g = 0$ V and that of $V_{ds} = 10$ V and $V_g = 5$ V, respectively. Here, Fig. 3(c) shows turn-on conditions. The Ga $2p_{3/2}$ peaks with applied V_{ds} of 10 V shifted to a higher binding energy than those without bias voltage. Furthermore, as the applied gate voltage increased from 0 to 5 V, the Ga $2p_{3/2}$ peaks shifted toward a higher binding energy. We found that the change of the potential caused by the applied V_{ds} and V_g was able to be observed clearly by using bias applied HAXPES. Then, the potential distribution images in the channel plane of a-IGZO TFT were extracted from Ga $2p_{3/2}$ montage spectra as a function of V_{ds} and V_g, as shown in Fig. 4(a)-(c). The peak positions of Ga $2p_{3/2}$ spectra were characterized by fitting with Voigt functions with a Shirley background. In the case of $V_{ds} = 0$ V and $V_g = 0$ V (Fig.4 (a)), the potentials in channel plane were almost the same, that is, the potentials in the a-IGZO channel are almost flat. On the other hand, for the potential distribution image of $V_{ds} = 10$ V and $V_g = 0$ V (Fig. 4 (b)), the potential gradually increases from the source electrode to the drain electrode. Moreover, by adding the applied gate voltage of 5 V (Fig.4. (c)), the high potential region near the drain electrode extended toward the source electrode. These potential distribution behaviors depending on the bias voltage can be effectively evaluated by using the bias applied HAXPES technique.

4. Conclusions

We presented a bias applied hard X-ray photoelectron spectroscopy (HAXPES) technique for an amorphous InGaZnO$_4$ thin film transistor (a-IGZO TFT) and successfully observed the potential distribution in the channel plane during transistor operation. We also observed that the change of the potential gradient in the direction of the channel length depended on source-drain voltage and/or gate voltage conditions. We demonstrated that bias applied HAXPES is very useful for evaluating the potential distribution image in the channel plane of the transistor devices.
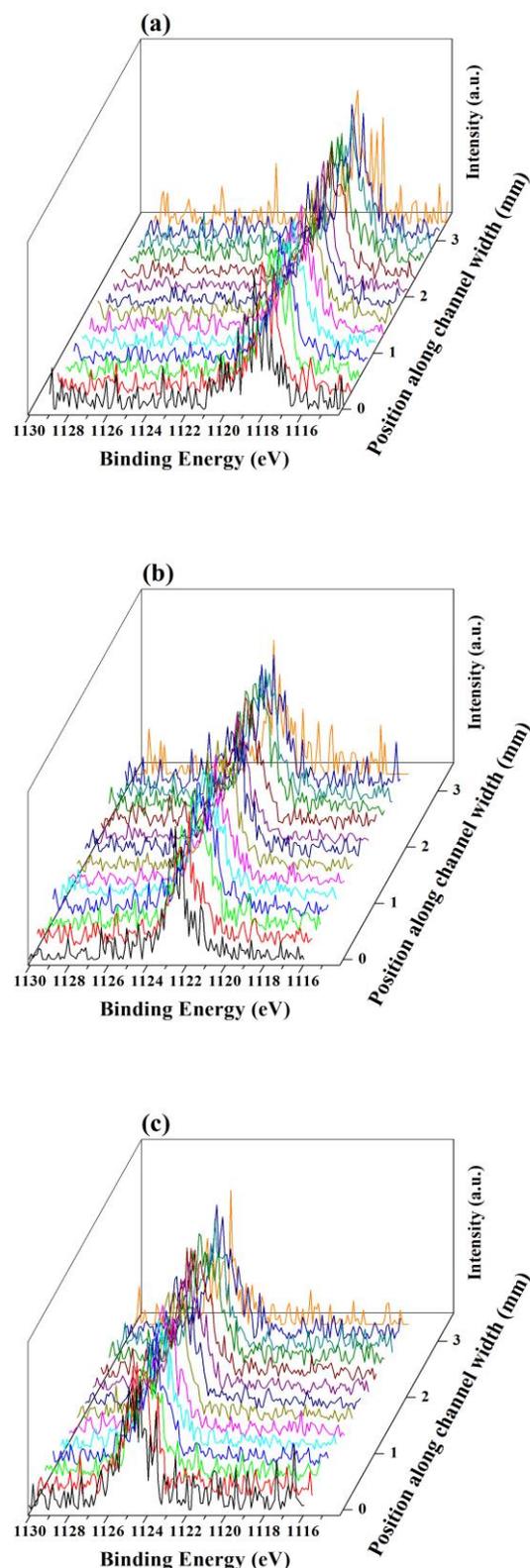
Fig. 3. (color online) Ga $2p_{3/2}$ montage spectra at the center of channel length (a) without bias ($V_{ds} = 0$ V and $V_g = 0$V), (b) with bias applied ($V_{ds} = 10$ V and $V_g = 0$ V), and (c) with bias applied *($V_{ds} = 10$ V and $V_g = 5$ V).*
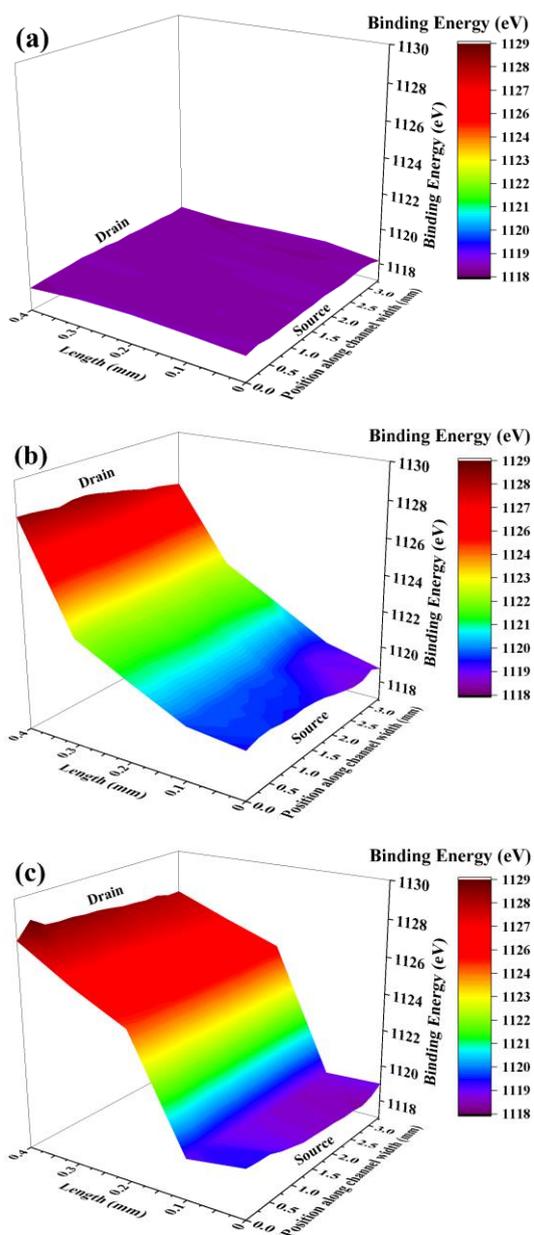
Fig. 4. (color online) Potential distribution image in the channel plane of a-IGZO TFT obtained (a) without bias ($V_{ds} = 0$ V and $V_g = 0$V), (b) with bias applied ($V_{ds} = 10$ V and $V_g = 0$ V), and (c) with bias applied ($V_{ds} = 10$ V and $V_g = 5$ V).

6. References

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Discussions and Q&A with Reviewers

Reviewer #1 Hideki Yoshikawa (National Insttitute for Materials Science)

[Q1_1]

It is not clear the reason why the authors used HAXPES for measuring the in-plane potential distribution, which can be obtained by soft X-ray XPS, Auger electron spectroscopy, secondary electron spectra and so on. The HAXPES is not the only way to do it. The authors should mention the reason in the section of Introduction.

[A1_1]

重要なご助言やご指摘を頂きまして大変ありがとうございました。

ご指摘頂きましたように、他の手法でも面内の電位分布を評価できる可能がある点は否めません（検出深さの点は別にして）。”これまで HAXPES では実際されていない”の一文を削除し、“表面変質層が存在し、その影響を低減するために HAXPES を使用している”、の内容を追記致しました.

Reviewer #2 Hisao Makino (Kochi Institute of Technology)

本論文は、産業上も重要な酸化物半導体薄膜トランジスタのデバイス動作下での HAXPES による評価について報告しています。印加電圧に依存した面内電位分布を内殻スペクトルのピークシフトとして観測しています。バイアス印加 HAXPES の半導体デバイス評価法としての高い可能性を示すものであり、JSA 誌への掲載に値する論文だと考えます。

[Q2_1]

本論文では、Ga 2p についてのみ検討されていますが、Ga 2p を選択した理由は何かありますか？
In や Zn の内殻スペクトルも Ga 2p と同様のシフトを示すのかどうか少し気になります。コメントをお願いします。

[A2_1]

IGZO を構成する元素の内殻スペクトルの内(光電子分光で一般的に使用される Zn 2p、 Ga 2p、 In 3d など)、最も(僅かな差ですが)強度が取れるものとして今回の測定では Ga2p を選択致しました。本文に

も記述を追記致します。

おそらく他の元素ピークも同じ挙動を示すのではないかと考えておりますが、これまでに測定したことがありませんので、現在のところ確実な事は分かりません。今後の課題としたいと考えております。