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Mechanism analysis of photoleakage current in ZnO thin-film transistors using device simulation

Mutsumi Kimura,1,a) Yudai Kamada,2,3 Shizuo Fujita,2 Takahiro Hiramatsu,4 Tokiyoshi Matsuda,2,4 Mamoru Furuta,4 and Takashi Hirao4

1Department of Electronics and Informatics, Ryukoku University, Seta, Otsu 520-2194, Japan; Joint Research Center for Science and Technology, Ryukoku University, Seta, Otsu 520-2194, Japan; and Innovative Materials and Processing Research Center, High-Tech Research Center, Seta, Otsu 520-2194, Japan
2Department of Electronic Science and Engineering, Kyoto University, Katsura, Nishikyo, Kyoto 615-8510, Japan
3Photonics and Electronics Science and Engineering Center, Kyoto University, Rohm Plaza, Katsura, Nishikyo, Kyoto 615-8520, Japan
4Research Institute for Nanodevices, Kochi University of Technology, Tosayamada, Kami 782-8502, Japan

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We analyzed the photoleakage current (I_{leak}) in ZnO thin-film transistors using device simulation. The dependences of I_{leak} on the location of light irradiation and drain voltage are reproduced by considering a Schottky barrier at the source contact using a two-dimensional device simulation. First, carrier generation is induced by light irradiation, the generated holes accumulate near the source contact, and some of these are captured in the donor traps. Next, the Schottky barrier becomes narrow, and electron injection increases via a tunneling effect. This discussion also suggests that the off-current is exceedingly low because the Schottky barrier prevents electron injection. © 2010 American Institute of Physics. [doi:10.1063/1.3502563]

Oxide-semiconductor thin-film transistors (TFTs), such as ZnO TFTs1 and amorphous In–Ga–Zn–O (a-IGZO) TFTs,2 are promising as next-generation giant micro-electronic elements because they are transparent devices, exhibit high performances, and can be fabricated on plastic substrates at low temperatures. Therefore, ZnO TFTs have been actively studied and extensively developed for not only flat-panel displays3,4 but also image sensors5 and transparent electronics.6,7 However, ZnO TFTs are not completely transparent devices even in the visible spectrum from the viewpoint of electrical influences, and a photoleakage current (I_{leak}) is observed upon blue-light irradiation.8 The large value of I_{leak} cannot be explained using simple physics of the carrier generation and should be deeply discussed.9

In this research, we analyzed the mechanism of I_{leak} in ZnO TFTs using device simulation. The dependences of I_{leak} on the location of light irradiation and drain voltage are reproduced by considering a Schottky barrier at the source contact using a two-dimensional (2D) device simulation. First, carrier generation is induced by light irradiation. Then, the generated holes accumulate near the source contact, and some of these are captured in the donor traps. Next, the Schottky barrier becomes narrow, and electron injection increases via a tunneling effect. This discussion also suggests that the reason the off-current (I_{off}) in ZnO TFTs is exceedingly low is because the Schottky barrier prevents electron injection even if the electron density is relatively high in ZnO films.

The device structures of the ZnO TFTs with light-shield layers to analyze the mechanism of I_{leak} are shown in Fig. 1.8

First, a Cr film is deposited as a gate electrode on a glass substrate, a SiNx film is subsequently deposited as a gate insulator using plasma-enhanced chemical-vapor deposition (PECVD) of SiH4 and NH3, and a SiOx film is sequentially stacked using PECVD of SiH4 and N2O. Next, a ZnO film is deposited as a channel layer using radio frequency magnetron sputtering at 150 °C, a SiNx film is sequentially stacked to protect the channel layer, and both films are simultaneously patterned using photolithography and dry etching. Afterwards, a SiNx film is further deposited as an interlayer insulator, an ITO film is deposited as source-drain electrodes, and a SiNx film is again deposited as an encapsulation insulator. Finally, a Cr film is deposited as a light-shield layer to restrict light irradiation within the channel layer. Three types of the light-shield layers are formed, where the entire, source-half, or drain-half regions of the channel layer are exposed to light irradiation. Here, the thickness of each film and gate width (W) and length (L) are indicated in Fig. 1.

The dependences of I_{leak} on the irradiation location and drain voltage (V_{dk}) measured using actual ZnO TFTs are

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a)Electronic mail: mutsu@rins.ryukoku.ac.jp.
The dependences of I_{leak} on the irradiation location and V_{ds} measured using actual ZnO TFTs are shown in Fig. 2. The wavelength and power of light irradiation are 370 nm and 200 μW cm⁻², respectively. Compared to the Si-based TFTs, an outstanding feature is that I_{leak} for the source-half irradiation is larger than that for the drain-half irradiation, as shown in Figs. 2(a) and 2(b). Another feature is that I_{leak} for the source-half irradiation increases as V_{ds} increases, whereas that for the drain-half irradiation does not increase very much even if V_{ds} increases as shown in Fig. 2(b).

The 2D device simulation is executed with carrier generation and tunneling effect models to analyze the mechanism of I_{leak}. Here, we assume a Schottky barrier at the source contact due to the difference in work functions between ZnO and ITO, which is 0.31 eV, and carrier generation is uniformly induced in the corresponding area to the light irradiation, which is 10¹⁸ cm⁻³ s⁻¹ by supposing that the quantum efficiency from the light irradiation to the carrier generation is 1%. The electron mobility is 3.0 cm² V⁻¹ s⁻¹, which is determined from the on currents of an actual ZnO TFT, and the hole mobility is 10⁻³ cm² V⁻¹ s⁻¹, which has a negligible influence on the following conclusion once the value is sufficiently low. The energy gap, electron affinity, dielectric constant, and effective state density in the conduction band are 3.28 eV, 4.29 eV, 8.12, and 4.5 x 10¹⁸ cm⁻³, respectively. The acceptor and donor trap densities are 1.5 x 10¹³ cm⁻³ eV⁻¹ and 3.0 x 10¹⁷ cm⁻³ eV⁻¹ at the midgap, respectively, which are extracted to fit the subthreshold and on currents without light irradiation.

The dependences of I_{leak} on the irradiation location and V_{ds} simulated using a 2D device simulation are shown in Fig. 3. It is found that the outstanding features above can be at least qualitatively reproduced, although they are not quantitatively accurate, which may be owing to the aforementioned assumptions. However, we think that the 2D device simulation correctly implements the mechanism of I_{leak}.

The spatial profile of the charge density near the source contact is shown in Fig. 4. Although that for the source-half irradiation is shown, the shapes for the entire and drain-half irradiation are similar except the values of the charge density. It is found that the charge density is high at the lower insulator interface near the source contact because the hole mobility is very low, and some of these are captured in the donor traps. Next, the positive charge lowers the energy band, the Schottky barrier becomes narrow, and electron injection is subject to a tunneling effect. Therefore, I_{leak} for the source-half irradiation becomes larger. Moreover, the Schottky barrier for the source-half irradiation becomes narrower as V_{ds} increases.

The mechanism of I_{leak} deduced from the measured and simulated results is shown in Fig. 6. First, carrier generation is induced by light irradiation. In the case of the source-half irradiation, generated holes are gathered and accumulate at the lower insulator interface near the source contact because the hole mobility is very low, and some of these are captured in the donor traps. Next, the positive charge lowers the energy band, the Schottky barrier becomes narrow, and electron injection is subject to a tunneling effect. Therefore, I_{leak} for the source-half irradiation becomes larger. Moreover, the Schottky barrier for the drain-half irradiation, which is of course much higher than without irradiation.

The dependences of the energy band across the source contact on the irradiation location and V_{ds} are shown in Fig. 5. Here, the spatial profile of the conduction band energy (E_c) along the dashed line in Fig. 4 is plotted. It is found that the Schottky barrier for the entire irradiation is narrower than that for the source-half irradiation, which is also narrower than that for the drain-half irradiation, whereas that without irradiation is terribly high. Moreover, the Schottky barrier for the source-half irradiation becomes narrower as V_{ds} increases.

The spatial profile of the charge density near the source contact.
barrier becomes narrower by applying $V_{ds}$, and the tunneling effect is enhanced. Therefore, $I_{\text{leak}}$ for the source-half irradiation increases as $V_{ds}$ increases, which is similar to the drain induced barrier lowering and can be named drain induced Schottky barrier narrowing.\textsuperscript{11} In the case of the drain-half irradiation, generated holes recombine during the long-time transport from the drain-half region to the source contact because hole mobility is low. The Schottky barrier remains wide, and electron injection is subject to thermal excitation. Therefore, $I_{\text{leak}}$ for the drain-half irradiation is smaller. Moreover, the electron injection via thermal excitation depends only on the height of the Schottky barrier and not the width. Therefore, the increase in $I_{\text{leak}}$ for the drain-half irradiation is small even if $V_{ds}$ increases.

This discussion also suggests that the reason $I_{\text{off}}$ in ZnO TFTs is exceedingly low is because the Schottky barrier prevents electron injection even if the electron density is relatively high in ZnO films. The Schottky barrier may become wider and prevent electron injection by applying a negative gate voltage ($V_g$) before the electron density is sufficiently reduced in ZnO films.

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\textsuperscript{10}Atlas, TFT, Blaze, and Luminous, Device Simulator, Silvaco International.

\textsuperscript{11}See supplementary material at http://dx.doi.org/10.1063/1.3502563 for some questions about the mechanism of $I_{\text{leak}}$. 

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure5.png}
\caption{(Color online) Dependences of the energy band across the source contact on the irradiation location and $V_{ds}$.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure6.png}
\caption{(Color online) Mechanism of $I_{\text{leak}}$ deduced from the measured and simulated results.}
\end{figure}