Preparation of Organic Light-emitting Field-effect Transistors with Asymmetric Electrodes

Tomo Sakanoue,[†] Eiichi Fujiwara,[††] Ryo Yamada,[†,††] and Hirokazu Tada*[†,††,†††]
[†]*The Graduate University for Advanced Studies, Department of Structural Molecular Science, Myodaiji, Okazaki, 444-8787*
[††]*Institute for Molecular Science, National Institutes of Natural Science, Myodaiji, Okazaki, 444-8787*
[†††]*JST-CREST, Japan Science and Technology Agency*

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Light-emitting field-effect transistors (LEFET) based on poly[2-methoxy-5-(2-ethylhexoxy)-1,4-phenylenevinylene] (MEH-PPV) were prepared with asymmetric electrodes of a Au/Cr source and an Al drain on a SiO_2 gate insulator (600 nm) through twice of photolithography and lift-off techniques. The light emission was observed when the gate voltages increased above −40 V at the drain voltage of −100 V. The luminous efficiency of the devices was significantly improved comparing to those with conventional electrodes of Au/Cr.

Organic field-effect transistors (OFETs) have attracted considerable attention because of their potential applications in low-cost integrated circuits[1] and flexible displays.[2] Since an ambipolar OFET, which can operate both in n- and p-channel modes, is especially useful for complementary circuits, various efforts have been done to prepare it. Dodabalapur et al. have pointed out the possibility that an ambipolar operation generates light emission through recombination of holes and electrons injected simultaneously into active layers.[3] Recently, visible light emission has been observed from OFETs based on tetracene[4] and polyfluorene.[5] Since these devices was conventional bottom contact type FET with Au/Cr electrodes, it was not suitable for simultaneous injection both of holes and electrons.

In the preceding work,[6] we demonstrated LEFETs based on poly[2-methoxy-5-(2-ethylhexoxy)-1,4-phenylenevinylene] (MEH-PPV) flims with bilayer electrodes of Au and Al. The LEFET with layered electrodes of Au/Al gave stronger luminescence than that with conventional electrodes of layered Au/Cr. The insertion of Al instead of Cr improved the electron injection effectively into the films. However, the Au/Al electrode caused a slight decrease in the output current, indicating that the Au/Al layered structure was not ideal for a simultaneous injection of holes and electrons.

A simultaneous injection of holes and electrons has been achieved by tuning the work function of cathodes and anodes in organic light-emitting diodes (OLEDs). It is well known that high work function materials such as gold and indium–tin-oxide are suitable for the hole injection whereas low work function materials such as calcium, magnesium and aluminum are preferable for the electron injection. The work function of the electrode is one of the most important factors in OFETs to determine the device characteristics. A p-type FET with gold electrodes showed higher performance than that with aluminum electrodes,[7] whereas an n-type FET improved its device performance by choosing aluminum and calcium for electrodes.[8]

In the present work, we prepared a LEFET of which different materials were used as source and drain electrodes to improve the balance of the number of carriers injected. A Au/Cr electrode was used for the hole injection whereas an Al electrode was for the electron injection.

Figure 1 shows a schematic view of the prepared device. A highly doped n^+-Si (100) plate was used as a gate electrode, on which an SiO_2 layer with the thickness of 600 nm was thermally grown. The asymmetric interdigital electrodes were prepared through twice of photolithography and lift-off processes. First, source electrodes of Au (20 nm)/Cr (10 nm) were formed on the SiO_2 layer. The guide lines for the succeeding processes were also formed on the substrate. The photo mask was then placed at the exact position referring the guide lines to prepare drain electrodes of Al (30 nm). The channel length and width of the electrodes used in the present study were 5 μm and 38 mm, respectively. The devices with symmetric electrodes of Au/Cr–Au/Cr and Au/Al–Au/Al were also prepared. MEH-PPV was purchased from Aldrich and purified by repeated re-precipitation. It was solution-casted onto FET substrates from a 0.5 wt % solution in chlorobenzene. The specimen was heated at 100 °C for 5 min in a nitrogen atmosphere to remove the solvent. Typical thickness of MEH-PPV was about 100 nm. All measurements were carried out in vacuum of 5×10^{-4} Pa at room temperature. Output characteristics of the FETs were measured with electrometers (Keithley 6487 and Keithley 487). The light intensity was detected with a Si photodiode (Hamamatsu, S1226-8BK) placed just above the device, through a glass window of the vacuum chamber.

The devices were operated in a hole accumulation mode. The field-effect hole mobilities of the devices with Au/Cr–Al,

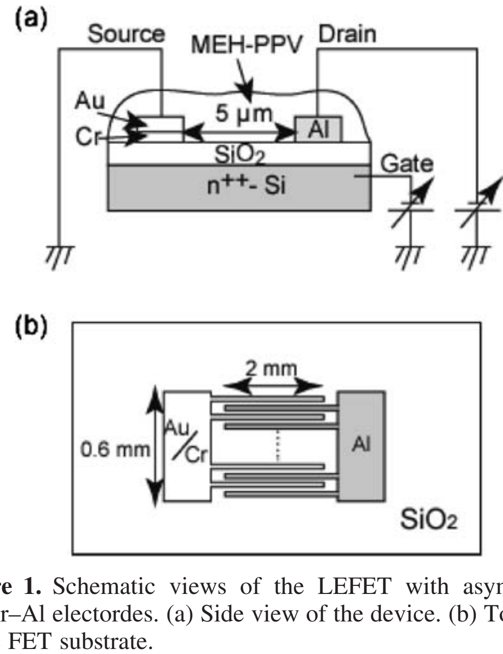

Figure 1. Schematic views of the LEFET with asymmetric Au/Cr–Al electordes. (a) Side view of the device. (b) Top view of the FET substrate.

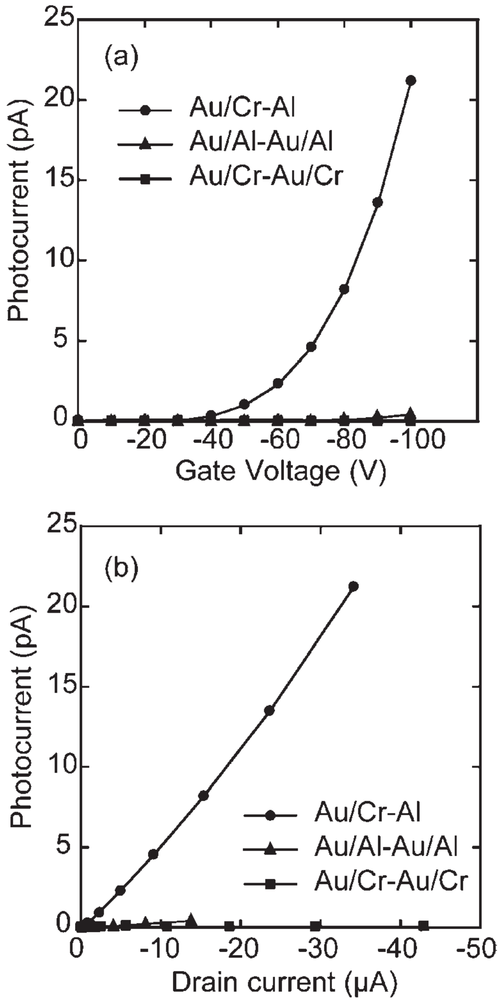

Figure 2. (a) Plots of the luminous intensity as a function of the gate voltage. The drain voltage was set at -100 V. (b) Plots of the luminous intensity as a function of the drain current. The gate and the drain voltages were set at -100 V.

Au/Cr–Au/Cr, and Au/Al–Au/Al were 4.2×10^{-4}, 5.5×10^{-4}, and 3.2×10^{-4} cm^2/Vs, respectively. These values for OFETs based on MEH-PPV are almost the same as those reported previously.[9,10] As the drain and gate voltages increased, orange light emission was observed from the FETs. Figure 2 shows luminous intensity of the device with asymmetric Au/Cr–Al electrodes as a function of the gate voltage (a) and of the drain current (b). The drain voltage was set at -100 V. The results for the devices with symmetric electrodes of Au/Cr–Au/Cr and Au/Al–Au/Al were also shown for comparison. The device with Au/Al–Au/Al electrodes showed weak light emission whereas no light emission was detected from the device with Au/Cr–Au/Cr electrodes. The insertion of Al instead of Cr improved the electron injection effectively to generate light emission as reported previously.[6] There can be seen significant improvements in the operating gate voltage and emission efficiency by using the asymmetric Au/Cr (source)–Al (drain) electrodes. The luminous efficiency of the devices with Au/Cr–Al was about 20 times higher than that of the device with Au/Al–Au/Al electrodes. The device with Al (source)–Au/Cr (drain) electrodes did not give light emission because of the high injection barriers for both holes and electrons. Since the work function of Al (4.06–4.26 eV) is lower than that of Au (5.31–5.47 eV) and Cr (4.5 eV),[11] an Al electrode is suitable for the electron injection to the lowest unoccupied molecular orbital of the MEH-PPV (2.9 eV)[12] as was demonstrated in many works on OLEDs. The use of the Al drain electrode improved the balance of the number of holes and electrons injected, which led to the efficient light emission.

Hepp et al., have shown that the light emission occurred from tetracene films in conventional bottom-contact type OFETs with symmetric Au/Cr electrodes.[6] They pointed out the possibility that the electron injections originated from the bad contact between organic layer and the drain electrode. It was considered that the work function of the electrode was not an important factor. Our results showed that the work function of the source and drain electrodes is a crucial factor to achieve efficient simultaneous injections of holes and electrons. When a negative bias voltage is applied to the gate, positive charges are induced at the interface between MEH-PPV and SiO_2. The holes are injected from the source electrode and transferred through the channel to the drain electrode. When high voltages are applied to the drain electrodes, the high electric field between the source and drain electrodes lead to band bending of the organic layer at the drain contact. As a result, the electrons can be easily injected into organic layer.

In summary, we prepared LEFET based on MEH-PPV with asymmetric Au/Cr–Al electrodes. The balance between the number of holes and electrons injected was improved by using Al electrodes, which lead to efficient light emission. It is important to choose appropriate materials for source and drain electrodes to inject both carriers efficiently. The LEFETs will provide the number of potential applications to optoelectronic organic devices.

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