The electrical characteristics of pentacene field-effect transistors with polymer gate insulators

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Abstract

We studied the electrical characteristics of pentacene-based organic field-effect transistors (FETs) with polymethyl methacrylate (PMMA) or poly-4-vinylphenol (PVP) as the gate insulator. PMMA or PVP was spin-coated on the indium tin oxide glass substrate that serves as gate electrodes. The source-drain current dependence on the gate voltage shows the FET characteristics of the hole accumulation type. The transistor with PVP shows a higher field-effect mobility of 0.14 cm²/Vs compared with 0.045 cm²/Vs for the transistor with PMMA. The atomic force microscope (AFM) images indicate that the grain size of the pentacene on PVP is larger than that on PMMA. X-ray diffraction (XRD) patterns for the pentacene deposited on PVP exhibit a new Bragg reflection at 19.5±0.2°, which is absent for the pentacene on PMMA. This peak corresponds to the flat-lying pentacene molecules with less intermolecular spacing.

1. Introduction

Organic thin-film transistors (OTFTs) have received significant research interests due to their potential advantages of large-area, flexibility, and low-temperature processing [1]. Over the past few years, their performances have increased tremendously so that they are already sufficient for certain low-cost electronic applications that requires an electrical performance similar to that of amorphous silicon TFTs [1-6].

In general, the organic materials such as small molecules or polymers are deposited in the amorphous structure that results in a low mobility due to the scattering and the localization of electronic states. Therefore, it is very important to enhance the structural order of an organic thin film for improving the carrier mobility. Since the morphology of organic materials is very sensitive to the surface properties of the substrate, we studied the morphology of the pentacene thin film deposited on polymer insulators such as polymethyl methacrylate (PMMA) or poly-4-vinylphenol (PVP) and electrical characteristics of pentacene field-effect transistors fabricated with polymer insulators as a gate dielectric layer. We found that the pentacene film deposited on PVP has the larger grain size and the higher field-effect mobility (about μ_{eff}~0.14 cm²/Vs) compared with the pentacene film on PMMA.

2. Experimental

The pentacene field-effect transistors were fabricated in a staggered-inverted structure as shown in Figure 1. The ITO glass was used as the substate and gate electrode. The gate dielectric layer was either PMMA or PVP on which a 100-nm-thick pentacene active layer was deposited with a deposition rate of 0.5 Å/s under the base pressure of 1×10^{-6} Torr. The gold (Au) source and drain contacts were deposited on top of the pentacene film through a shadow mask. The channel length and width are 50 μm and 2 mm, respectively.

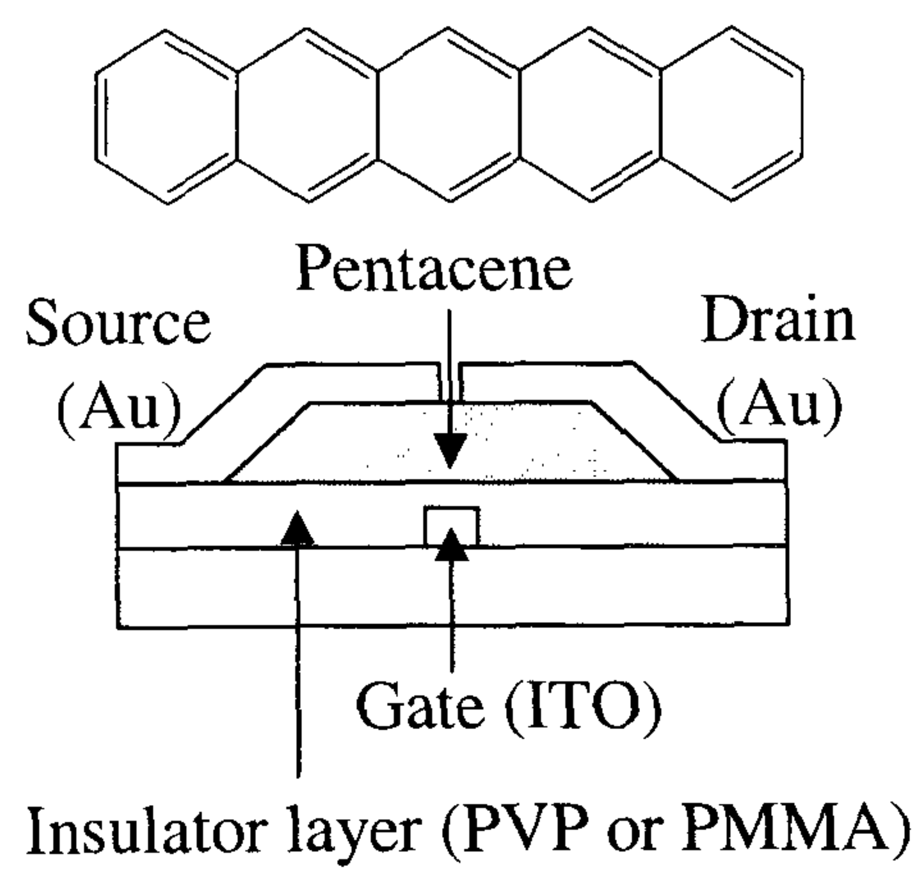

Figure 1. Schematic cross section of a pentacene field-effect transistor with a polymer (PVP or PMMA) gate insulator on an ITO glass substrate. The channel length and width are 50 μm and 2 mm, respectively.

The PMMA gate dielectric layer was deposited onto the prepatterned ITO glass by spin coating from a 4 weight % solution of PMMA and chlorobenzene. The PVP gate dielectric layer was deposited was deposited from a 15 weight % solution of poly-4-vinylphenol and propylene glycol monomethyl ether acetate (PGMEA) followed by curing at 200 ℃ for 2 hours. The spin speed was 2000 rpm and the thickness of the gate insulator was 922 nm and 945 nm for PVP and PMMA, respectively. On top of the polymer gate dielectric layer the pentacene active layer and then Au source and drain electrodes were deposited by thermal evaporation under the base pressure of $1x10^{-6}$ Torr. The pentacene was purchased from Aldrich and used as received. The surface morphology of the pentacene film was examined by atomic force microscopy (AFM). The transistor characteristics were measured with Keithley 236 source measure unit and Keithley 2400 source meter.

3. Results and discussion

Figure 2 shows the AFM images of the pentacene thin film deposited on the ITO glass, PMMA, and PVP layer. The grain size of pentacene is very small when deposited on the bare ITO surface. However, the pentacene film grows in a polycrystalline structure on PMMA or PVP with the grain size of an order of μm. The result indicates that pentacene adheres well to both polymers and therefore the molecular interaction between pentacene and polymer increases the growth rate in the lateral direction, resulting in the large grain sizes.

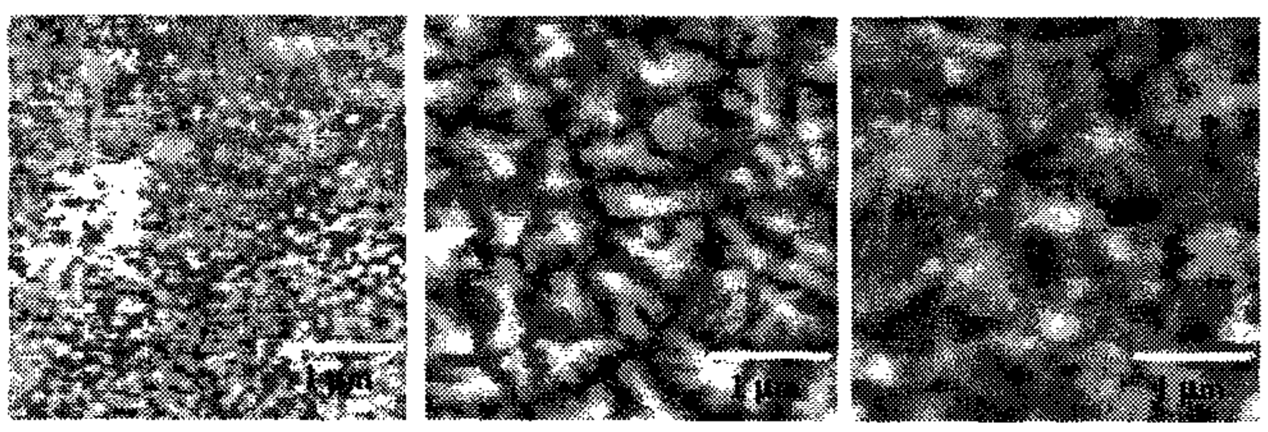

Figure 2: AFM images of pentacene thin film on ITO glass (left), PMMA (center) and PVP (right). The pentacene layer has an average thickness of 100 nm.

Figure 3 shows the x-ray diffraction pattern for a pentacene layer deposited onto a bare ITO glass, PMMA and PVP coated ITO glass substrates. We observed a strong X-ray reflection peak centered at 2θ=5.89°, which corresponds to the (001) planes of the pentacene crystals in the polycrystalline film [8]. It was reported that the long crystal axis of pentacene crystals are nearly normal to the substrate plane [8].The interplanar spacing is estimated as 14.9 ± 0.1 Å. Interestingly, the pentacene film deposited onto PVP exhibits a new Bragg reflection at 19.5±0.2°, which is absent for the pentacene film deposited onto either PMMA or bare ITO substrate. This peak was also reported for the pentacene film deposited on the octadecyltrichlorosilane (OTS) - treated SiO_2 substrate [9]. It was identified as arising from (110) and ($\bar{1}11$) reflection of pentacene [9], with an interplanar spacing of ~ 4 Å These features indicate that some fractions of the pentacene molecules on PVP are lying flat on the substrate surface, implying an improved adhesion of pentacene to the PVP surface compared with PMMA.

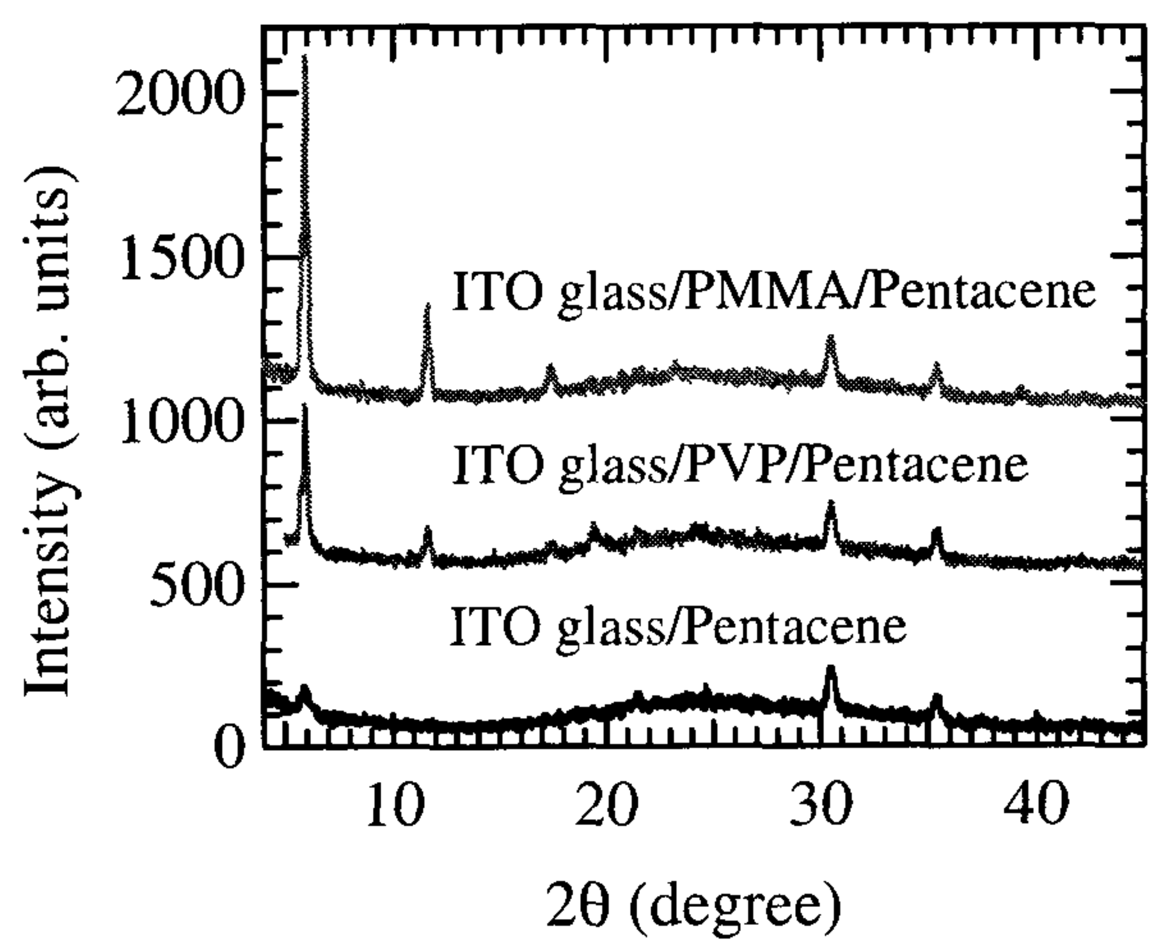

Figure 3: X-ray diffraction patterns of the pentacene film on ITO glass, PMMA and PVP.

Figure 4 shows the drain-source current (I_{DS}) versus drain-source voltage (V_{DS}) characteristics for several values of gate voltage (V_{GS}) for pentacene TFTs using PMMA or PVP as gate insulators. The I_{DS} – V_{DS} characteristics indicate a p-channel accumulation type FET. Under a given gate voltage V_{GS}, the drain-source current is about an order of magnitude higher for the device with the PVP gate insulator compared to that with the PMMA gate insulator. The result indicates a higher field-effect mobility μ_{FET} for the pentacene on PVP. Since the XRD data in Fig.3 shows that the orientation of the pentacene crystal on PVP lies flat with less interplanar spacing, the higher mobility is attributed to the better overlap of in-plane π-electron orbitals of pentacene molecules. The saturation behavior is slightly better for the PMMA gate insulator due to the less leakage current compared to the PVP gate insulator (see Fig. 5).

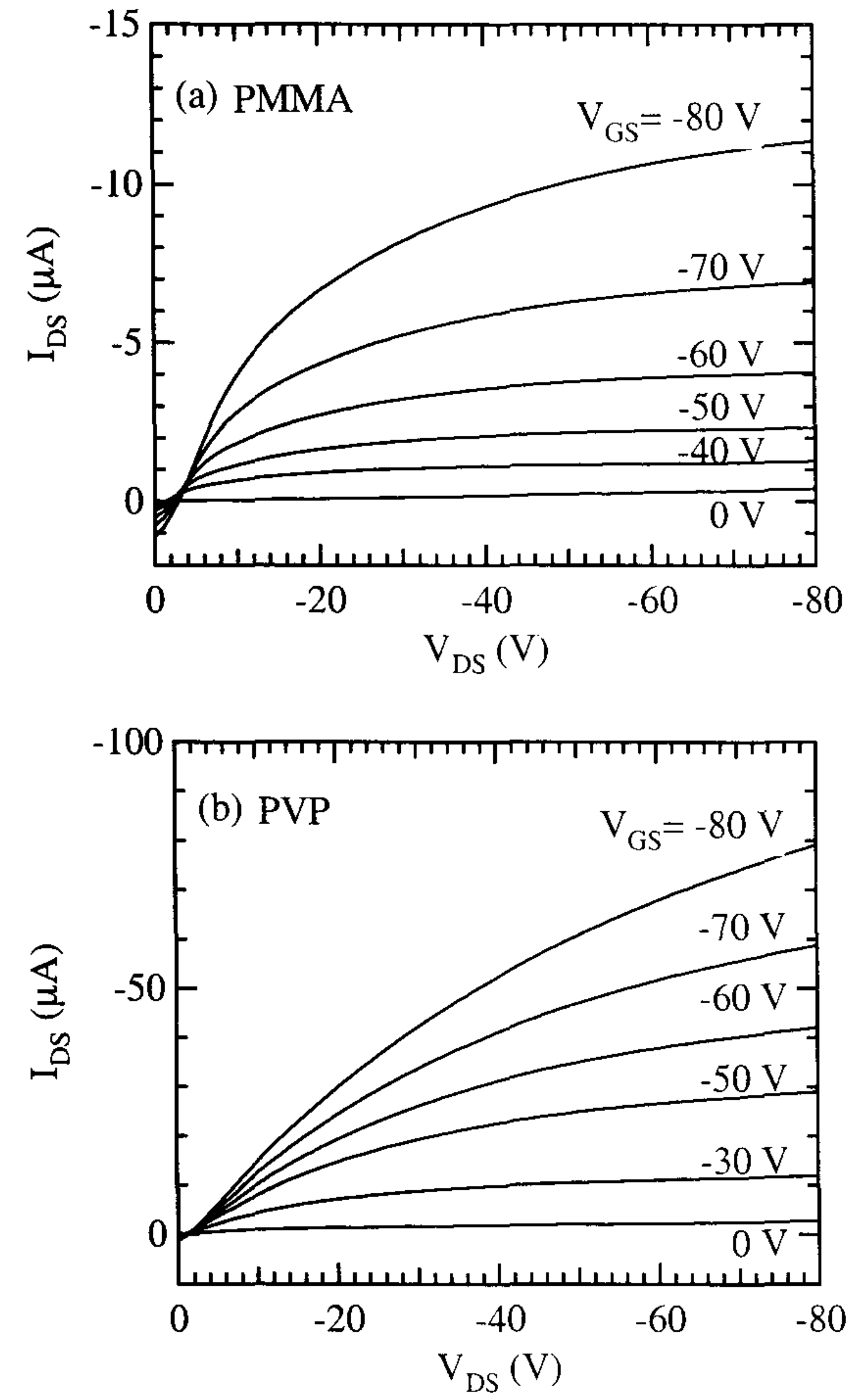

Figure 4. Drain-source current (I_{DS}) vs drain-source voltage (V_{DS}) transfer characteristics at different gate-source voltages (V_{GS}) for the pentacene FETs with PMMA (a) or PVP (b) as a gate insulator.

The field effect mobility μ and the threshold voltage V_T can be extracted from the transfer characteristics. Figure 5 plots the $(I_{DS})^{1/2}$ versus V_{GS} characteristics (a) and I_{DS} versus V_{GS} characteristics (b) of pentacene-channel FETs. The I_{DS} versus V_{GS} curves were obtained by scanning V_{GS} from +40 to –80 V in the forward and reverse direction. Devices using pentacene on different gate insulators of PVP and PMMA are compared. In the saturation regime of the drain-source current, the field-effect mobility for the PVP gate insulator the hole mobility is μ_{FET} =0.15 cm^2/Vs at V_{DS} = -60 V and the on/off current ratio is about 10^2, while for the PMMA gate insulator device μ_{FET} =0.045 cm^2/Vs at V_{DS} = -60 V and on/off current ratio is about 10^2. As demonstrated in Fig. 4, the higher mobility of pentacene on PVP indicates the better overlap of π-electron orbitals of pentacene molecules. However, the FETs using PMMA and PVP show a lot of leakage current. In addition, the threshold voltage is quite large due to low dielectric constant of PMMA (ε = 2.5 ~ 4.5) and PVP (ε = 3.6) [7]. Therefore, further improvement is required.

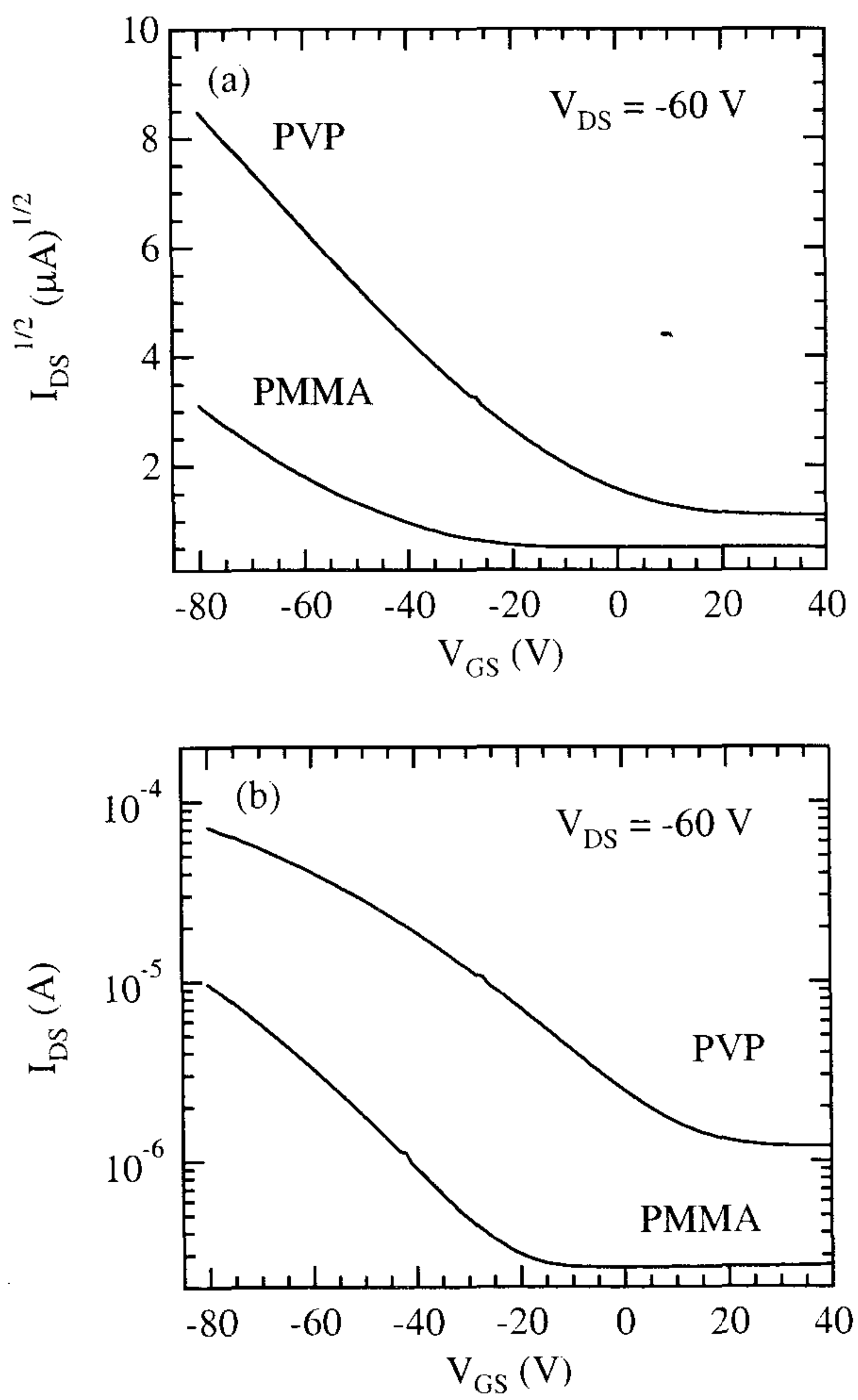

Figure 5. $I_{DS}^{1/2}$-V_{GS} (a) and I_{DS}-V_{GS} (b) characteristics at V_{DS} = -60 V for the pentacene-channel FETs with PMMA or PVP as a gate insulator.

4. Conclusion

We have reported the enhancement of the FET characteristics of the pentacene-channel FETs using polymer gate insulators of PVP or PMMA. The pentacene-channel transistors show the p-type enhancement characteristics. Devices with pentacene deposited on PVP show a higher field-effect mobility of μ_{FET} =0.14 cm^2/Vs compared with 0.045 cm^2/Vs for that on PMMA. The x-ray diffraction patterns of the pentacene deposited on PVP show a fraction of flat-lying molecules with less interplanar spacing compared to the pentacene deposited on PMMA. Therefore, the higher mobility is attributed to the better overlap of the π-electron orbitals of pentacene molecules. The result indicates the importance of the morphology and molecular configuration on the mobility of the organic transistors.

5. Acknowledgements

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