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High-performance ultra-low leakage current graphene-based screen-printed field-effect transistor on paper substrate

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Abstract. Exploiting the advantages of additive patterning process over complex fabrication processes, herein we report the fabrication of field-effect transistor (FET) using the screen-printing method. The graphene conductive composite dielectric ink as the channel and the dielectric layer respectively was screen printed on cellulose paper substrate. The fabricated device shows the hole and electron mobility of 135 cm^2/V s and 98 cm^2/V s respectively with an ultra-low leakage current of ∼25 nA. The proposed technique can be used for large-scale roll-to-roll commercial manufacturing of disposable FET-based sensors such as temperature and IR sensors, health monitoring devices etc.

Keywords. Graphene field effect transistor; gate leakage current; screen printing; mobility.

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1. Introduction

Graphene-FETs are one of the thrust areas in current research by scientists around the world and is demonstrated for various applications [1–4]. Compare to rigid substrates, flexible substrates can be used for several applications such as flexible displays [1], human motion detectors [2], strain sensors [5], artificial retina [4], etc. Moreover, graphene-based FETs using paper substrate have already demonstrated high performance [2,6–9] with complex fabrication processes which is not suitable for the roll-to-roll printing of the devices to be used for commercial purpose. Generally, the graphene layer is obtained by growing a layer through chemical vapour deposition (CVD) over a copper foil followed by transfer to the target substrate, which involves the usage of chemicals like polymethyl methacrylate (PMMA), etc., which are non-biodegradable. Another method for depositing graphene layer is to prepare a suspension and deposit by Langmuir–Blodgett method or spin coating, but the rate of delivering the sample is low. Also, these methods are not easily scalable, not repeatable, not suitable for bulk manufacturing and do not have satisfactory performance in terms of mobility, gate leakage current, etc. [10–13]. In addition to this, reliability of the FET performance depends upon the gate leakage current. Commercial FET has shown gate leakage current up to 100 nA [14].

Keeping all these in view, in this paper, to the best of our knowledge, for the first time, we present a promising method to fabricate screen-printed graphene-based FET. The presented structure consists of graphene and composite graphene dielectric used as the channel and dielectric with ultra-low leakage current.

2. Ink formulation and device fabrication

Graphene nanopowder was bought from United Nanotech, India and other materials used for ink formulation were borrowed from CYMK inks LLP, India. Graphene ink was formulated by liquid phase formulation using the bead mill method with a multilayer structure. The resistance of graphene sheet was calculated to be $9.3746 \times e^2\ \Omega/sq$, and accordingly, the conductivity is $10.6 \times e^{-4}$ Simens/sq [15]. Dielectric ink was formulated using graphene powder (10 g), commercially used HS Medium resin (70 g) and MEK (25 g). The Raman spectroscopy was performed using DXR-2, Raman microscope to confirm the formation of graphene-based channel and gate dielectric. The prepared ink was screen printed on the paper substrate

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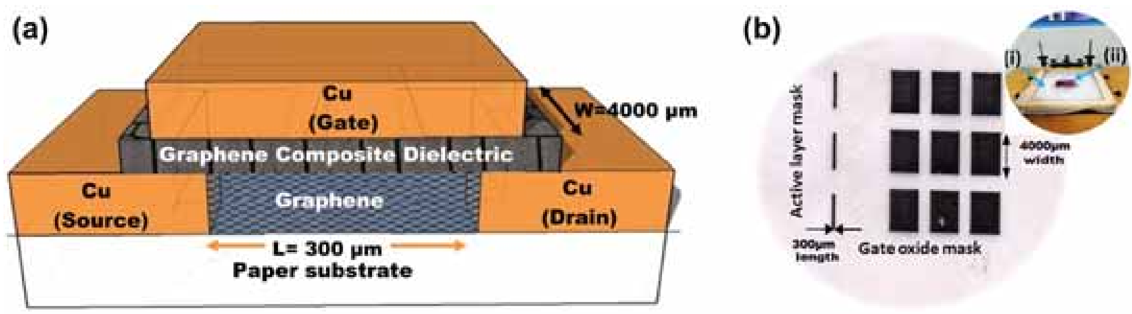

Figure 1. (**a**) Cross-section of the device fabricated. The cellulose paper is used as paper substrate material over which the drain and the source electrodes are deposited by thermal evaporation using prefabricated mask. Another active layer mask is used to deposit graphene as the channel material in between electrodes above which gate oxide mask is used to deposit the graphene oxide as the dielectric material. (**b**) Active layer mask and gate oxide mask used to deposit graphene as the channel material and gate oxide as the dielectric using screen-printing set-up as shown in the inset; (i) screen cloth and (ii) five-star film masks used.

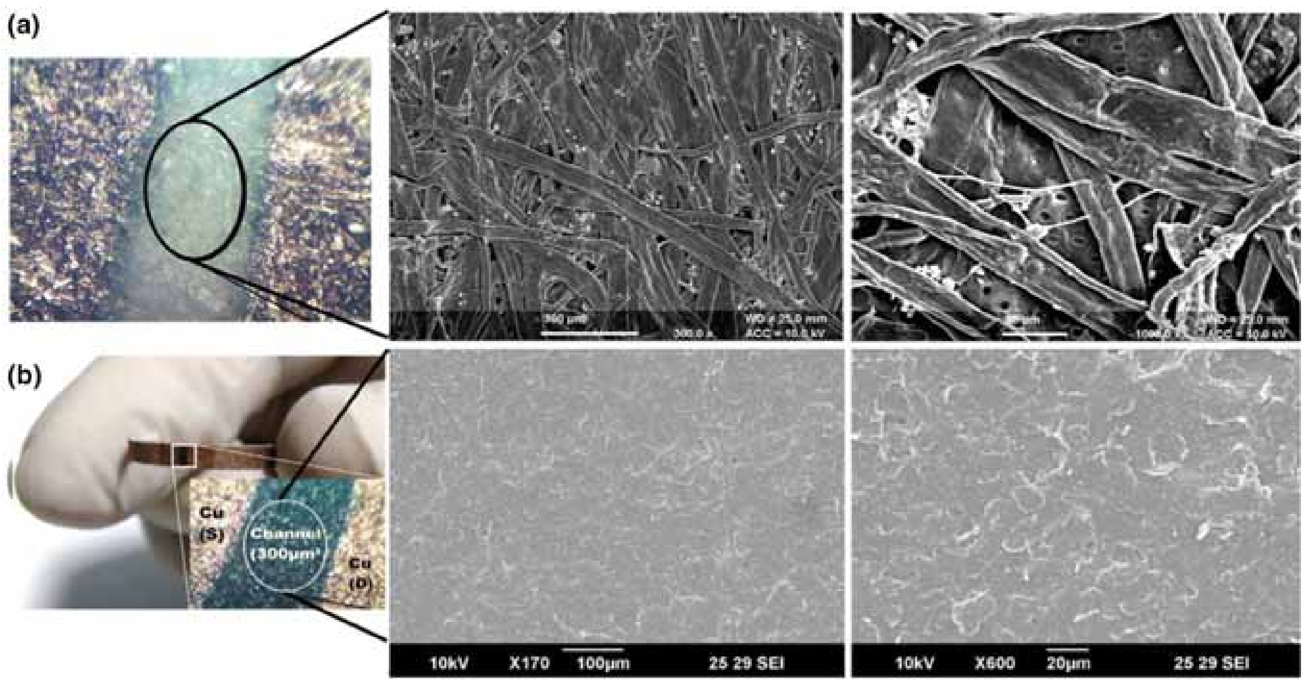

Figure 2. Pre-fabricated device with the source and the drain contact electrode (**a**) without and (**b**) with graphene active layer in between (inset shows SEM image of the channel area).

between the source and the drain electrodes fabricated using thermally deposited copper pellets with 99.999% purity (Sigma Aldrich, USA). Schematic of the fabricated device is shown in figure 1a. The graphene active area and the graphene gate oxide were developed by the screen-printing set-up using a mask, as shown in figure 1b. The screen-printing process involves the use of polyester screen mesh (120 mesh size used in the present work) with an aperture size of 149 μm. With the help of rubber squeeze, the formulated ink paste has been squeezed manually on the surface of the mesh via predefined pattern formed by photolithography of photostensil five-star film below which the paper substrate is placed. The design of the shadow mask was prepared in design-pro with bitmap format and was printed on the butter paper from the laser printer.

Figures 2a and 2b show the prefabricated device without and with graphene active layer deposited in between the source and the drain electrode (inset shows the microscopic image of the channel area) deposited by thermal evaporation method. The surface morphology of graphene ink printed on cellulose paper was analysed by Scanning Electron Microscope and was found uniform with low deformations, as shown in the inset image.

Table 1. Comparison with state-of-art in literatures.

Ref.	Channel fabrication method	Channel material (Dielectric material)	w/l ratio	Mobility ($cm^{-2}/V\ s$)	Gate leakage current
[6]	Pencil on paper with ion gel	Graphite (Ion gel)	3	$\mu_h = 106$ $\mu_e = 59$	0.2 μA
[2]	Pencil on paper	Graphite (Paper)	0.5	$\mu_h = 191$ $\mu_e = 167$	150 nA
[9]	Graphite with a shadow mask	Highly oriented pyrolytic graphite (SiO_2)	0.3	1.96×10^3 Drude formula	NA
	Graphene with lithography	Graphene (SiO_2)	0.5	16.9 Drude formula	NA
[16,17]	Graphene by transfer of the pattern	Graphene (Al_2O_3)	NA	$\mu_h = 300$ $\mu_e = 230$	NA
		Graphene (Ion gel)	NA	$\mu_h = 203$ $\mu_e = 91$	NA
		Graphene (Ion gel)	NA	$\mu_h = 892$ $\mu_e = 628$	NA
		Graphene (SiO_2)	NA	$\mu_h = 828$ $\mu_e = 189$	NA
[18]	Graphene by paintbrush	Graphene (Paper)	0.2	$\mu_h = 100$ $\mu_e = 52$	NA
This work	Screen printing	Graphene (Graphene composite ink)	13.3	$\mu_h = 135$ $\mu_e = 98$	~25 nA

3. Experimental results and discussion

The electrical performance of the device was analysed by determining the drain characteristics, gate leakage current, and transfer characteristics. All the measurements were carried out in vacuum conditions which prevent hygroexpansion process.

Prior to the measurements, the device was retained in vacuum conditions to avoid any impact of humidity and pressure. The drain characteristics show a linear increase in the drain-to-source current over the range of − 40 to 40 μA for a change in the drain-to-source voltage of − 1 to 1 V with considerable shift for a different gate-to-source voltage as shown in figure 3a. The gate leakage current was determined to be 25 nA, as shown in figure 3b, which is negligible compared to the channel current and is one of the significant factors of the fabricated FET. The transfer characteristics of the device demonstrate ambipolar behaviour [16,17] which is shown in figure 3b. The small asymmetry in the curve shows the difference in the concentration of electron and holes in the device, which may be due to the absorption of moisture in the form of water. The Dirac point is shifted towards the positive region of the gate voltage due to the addition of water molecules from the atmosphere humidity during the fabrication process [8].

Based on FET transconductance and capacitance of the gate dielectric, the mobility (μ) of FET was estimated as follows:

$$\mu = \frac{g_m}{(w/l) C V_{ds}}. \tag{1}$$

Here, $g_m = 1.469 \times 10^{-5}$ A/V and 1.064×10^{-5} A/V for holes and electrons respectively; $(w/l) = 13.3$, $C = 8.13\,nF/cm^2$ (measured by the sandwiched geometry of the dielectric ink between the metal electrodes) and $V_{ds} = 1$ V.

On calculation, mobility for holes and electrons are found to be $\mu_h = 135\,cm^2/V\ s$ and $\mu_e = 98\,cm^2/V\ s$, respectively. The observed value of mobility even at large w/l ratio, in comparison to the reported value in literatures (as tabulated in table 1) is probably due to the large transconductance (g_m) of the device.

From the futuristic point of view, the scaling of GFET may further be improved using high-resolution screen mask and screen cloth with higher mesh count. Furthermore, highly conductive water-based graphene ink may lead to the printing of all components of FETs, including source, drain, and gate contact along with the channel and the gate oxide which may lead to environment-friendly disposable devices.

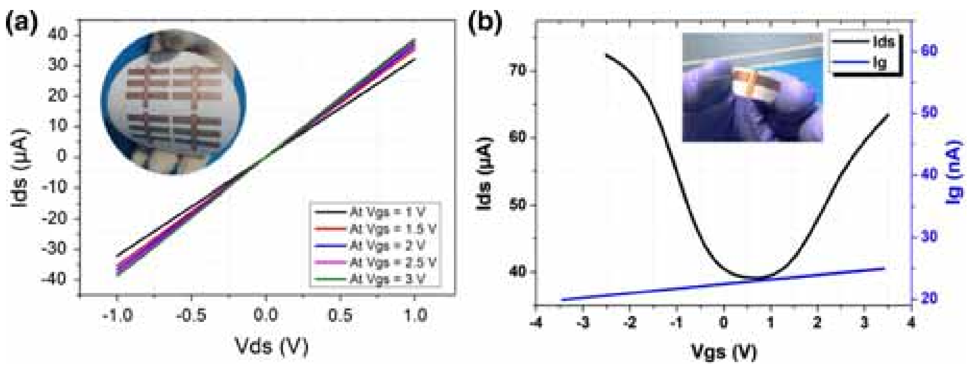

Figure 3. (**a**) Drain characteristics with the inset showing the array of fabricated devices and (**b**) transfer characteristics with gate leakage current of graphene FET (inset showing the fabricated device).

4. Conclusion

In conclusion, we have demonstrated a new approach for the fabrication of graphene conductive and dielectric ink using the screen-printing method to form FET on flexible paper substrate. The hole and the electron mobilities of the fabricated device are 135 cm^2/V s and 98 cm^2/V s respectively with an ultra-low leakage current of ~25 nA. The proposed method will lead to the large-scale production of flexible electronics devices. The proposed method can also be used for bulk manufacturing of graphene-based disposable sensors such as temperature sensors, IR sensors, health monitoring devices, etc.

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