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Flexible field effect transistor construction techniques, a brief review

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ABSTRACT

Since the Flexible field effect transistor (F-FET) is the building block of any sophisticated electronic circuit, particularly in the area of wearable electronics and biomedical sensors, it has drawn a lot of attention recently. It is usually fabricated using stretchable semiconductors over polymeric substrates. This paper displays a brief overview of the current fabrication techniques of the F-FET, specifically in terms of the type of substrates and nano semiconductor technologies. As for the applications, flexible devices such as graphene, carbon nanotubes, and nanoparticles seem to be a candidate for future flexible devices due to their excitant electronic and stretchable characteristics.

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1. Introduction

1.1 F-FET structure

Typically, F-FET consists of a source, drain, and gate. It constricts on an insulating substrate. The source and drain are deposited on a semiconductor and connected to an external power supply through conductive electrodes, usually gold, copper, or silver. The gate of the FET is usually fabricated either on the top or the bottom of the substrate, that's why the FET structure is called the top or bottom gate (Fig. 1).

Basically, the charge carriers flow through the FET under the control of the applied gate voltage. The relationship between V_{GS} and I_{DS} is $I_{DS} = \mu(WC/2L)(V_{GS} - V_T)^2$, where I_{DS} is the current that is flowing from drain to source, C is the insulator capacitance, V_T is the threshold voltage, W is the width of the channel, and L is its length, Schneider, et al. [1].

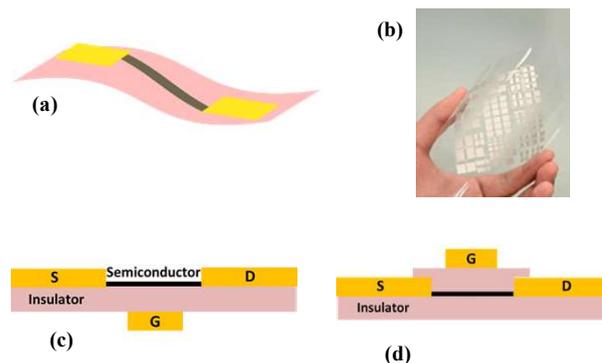


Figure 1. FET structure: (a) with a bottom gate; (b) with a top gate; (c) F-FET with a flexible substrate; (d) Electronics on a flexible substrate

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1.2. Effect of bending on F-FET characteristics

Based on reported articles [2, 3], bending an F-FET causes two potential effects on the F-FET properties. First, it affects the I-V characteristic. Second, it affects the electron mobility of the F-FET. As illustrated in Fig. 2, the effect of bending is also depending on whether the bending is upward or downward. Remarkable differences have been seen in the electron mobility and the I-V curve between the downward bending (Fig. 2-a) and upward bending (Fig. 2-b). However, bending in the same direction leads to a very slightly changing in the F-FET properties.

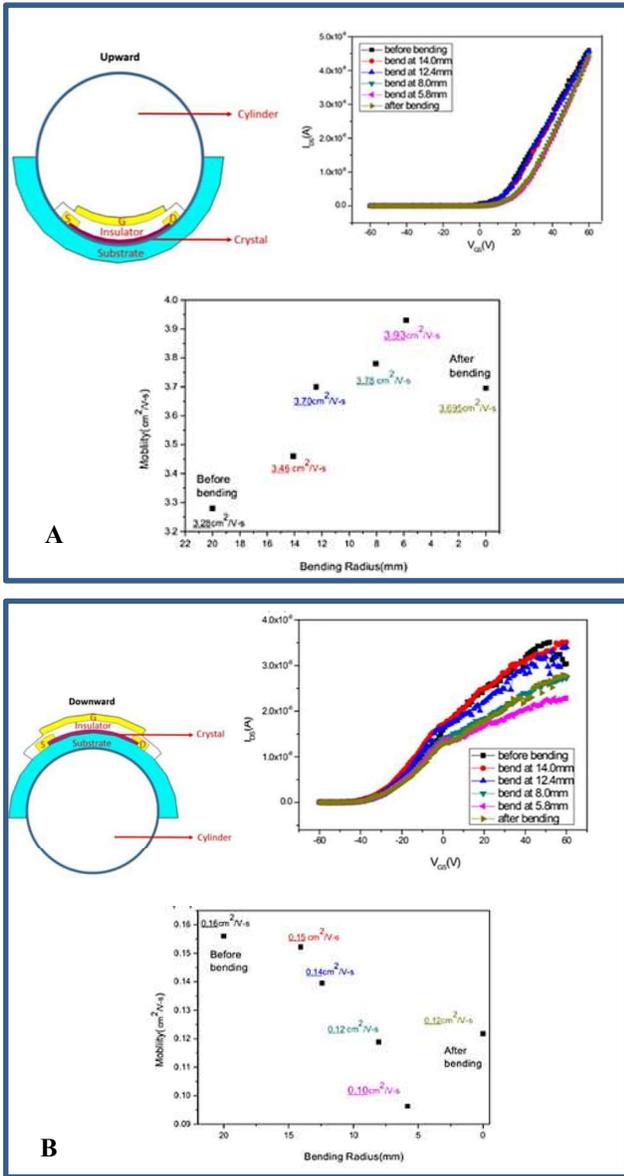


Figure 2. (a) Schematic of downward bending of F-FET on PET substrate and corresponding I-V curve and electron mobility. (b) Schematic of upward bending of F-FET on PET substrate and corresponding I-V curve and electron mobility [4].

2. Types of flexible substrates

The material of a substrate decides the mechanical properties such as the strain and bending angle of the fabricated device. This is why the first thing that one needs to think about is substrate flexibility. The strain of a substrate is a function of its thickness, Young’s Modulus, and the type of deposited layers upon the substrate. The strain can be calculated by Yin et al. [5]:

$$S = \frac{(t_L + t_s) \left(1 + \frac{2t_L}{t_s} + \frac{Y_L \times t_L^2}{Y_s \times t_s^2} \right)}{2R + \left(1 + \frac{t_L}{t_s} \right) \left(1 + \frac{Y_L \times t_L}{Y_s \times t_s} \right)}$$

Where t_L and t_s are the thicknesses of the layer and the substrate respectively. While Y_s and Y_L are Young’s modulus of the substrate and the layer respectively and R is the radius after bending. It should be mentioned that the conductivity of the device is dimension dependent, which could be changed with bending or stretching [5, 6].

2.1. Polyethylene terephthalate (PET) substrate

Basically, PET is a polyester family. Depending on the thickness, PET could be rigid or flexible. It is lightweight, low cost, thermally stable, and moisture resistant Bach et al. [7]. PET has a Young modulus of 2800-3100 MPa, a dielectric constant of 60 Kv/mm, and a melting point of around 250 °C Faraj et al. [8]. It has been used in the design of flexible substrates for several applications such as flexible antennas [9, 10], biosensors [11, 12] wearable sensors Gao et al. [13], and flexible electronics [14-16]. Due to its nice optical properties (optical transmission of 85%) and flexibility under bending conditions MacDonald [17]. PET becomes a candidate for flexible displays. Optimal printed thickness and spacing for electronic application and also the thermal operation of the PET substrate have been reported by Riheen et al. [16], it was proved that the optimal spacing of inkjet printing for electronic application is around 20 μm and thermally durable at 120 °C. Fig. 3-a shows a photo image of the PET, while Fig. (3-b) is the AFM image of the PET, it shows the mean square of the surface roughness, which is about 13.5 nm [17].

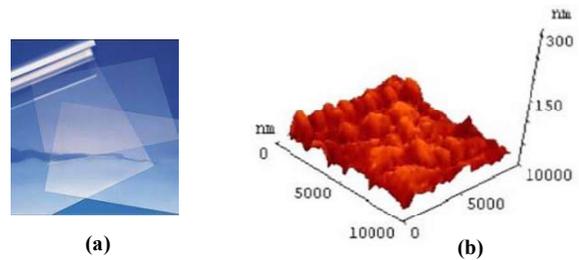


Figure 3. (a) PET sheet (b) Surface morphology of PET [17].

2.2 Polydimethylsiloxane (PDMS) substrate

PDMS has been used as a flexible substrate due to its transparency, tailoring, chemical stability, and flexibility. In addition, it is easy to construct with the desired thickness Qi et al. [18]. It has a Young modulus of 1.4 MPa and dielectric strength of 27 kV/mm. These properties make PDMS used in microfluidics and electronic devices [18, 19]. Furthermore, PDMS is a biocompatible material, meaning similar to the human tissue,

this makes it favorable in the construction of biosensors Victor et al. [20]. Fig. 4 shows a photographic image of a PDMS layer.



Figure 4. Flexible PDMS substrate.

2.3. Polyimide substrate

Polyimide is another interesting flexible polymeric material that has been used as a flexible substrate. In fact, multiple properties made Polyimide an excellent choice such as flexibility, lightweight, low cost, relatively high operating temperature (up to 400 °C) and moisture resistance, Young modulus of 4 GPa, and a dielectric constant of 3. It has been used as a flexible substrate in many applications, for example, solar Caballero et al. [21] cells, flexible printed circuits Wang et al. [22], biomedical probes, and wearable devices [23, 24]. Fig. 5-a shows one of the applications of polyimide in biomedical probes. Fig. (s-b) is the AFM image of the polyimide, it shows the surface roughness is 22.52 nm, which is accepted for many applications.

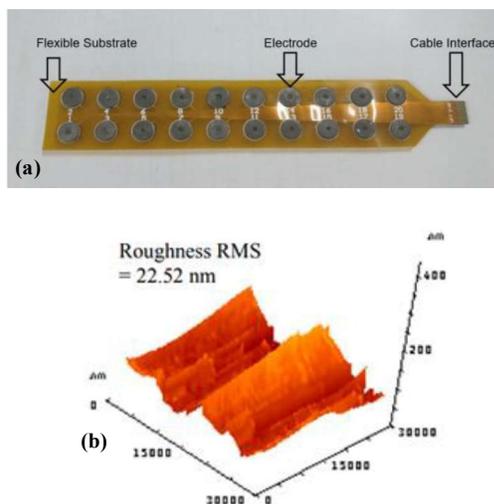


Figure 5. (a) bio-medical probe with a flexible Polyimide substrate (b) AFM image of a polyimide sheet with 22.52 nm surface roughness [25, 26].

3. Type of flexible semiconductor materials for F-FET

3.1. Carbone nanotube (CNT)

CNT has been used for several applications due to its excellent electronic and mechanical characteristics. High electron mobility, $(2-6) \times 10^4 \text{ cm}^2 / (\text{V} \times \text{s})$, high stable current of 10^9 A/cm^2 , and high electrical conductivity (10^6 to 10^7 S/m) Mora et al. [27] make CNT a promising for the design of high-speed F-FET [28-31]. It has also been used as a sensor, such as humidity and piezoelectric sensors [32-35]. Additionally, the CNT's

mechanical properties have been studied and Young's modulus was calculated to be on the order of 1 TPa and the tensile strength of CNT-polymer composite of 11-63 GPa Arash et al. [36]. These exceptional properties made it compatible with the applications of flexible devices Esawi et al. [37]. CNTs can be deposited on a flexible substrate using spray coating. This method is the simplest, most low-cost, and most reliable method Abdelhalim et al. [38].

3.2. 2D materials

Graphene is a good example of 2D material, a hexagonal structure (Fig. 6), that was invented by Geim and his group using mechanical exfoliation [39, 40]. Since the invention of graphene, many research groups have worked on it to investigate its properties and potential applications. Basically, graphene has a lot of amazing electrical characteristics, for example, high charge mobility ($200 \text{ cm}^2/\text{V}\times\text{s}$) Bolotin et al. [41], excellent mechanical characteristics (Young modulus of 1 TPa), and nice thermal conductivity (3500W/mK to 5000W/mK) Hu et al. [42]. Therefore, graphene is nominated for future sensors and electronics [28, 43-49]. S. Park et al. has fabricated a F-FET that has a 95 GHz cutoff frequency Park et al. [50]. While F. Lui and his group constructed an F-FET with a large flexible area Liu et al. [51].

Graphene can be grown directly on a flexible substrate by plasma-enhanced chemical vapor deposition (PE-CVD) Lee et al. [52]. Whereas the simplest method for graphene deposition on the flexible substrate is by transfer method. In this method, a CVD graphene is grown on metal such as copper then a thin film of Poly(methyl methacrylate (PMMA) polymer, the e-beam resist, is deposited on graphene. Then the metal etched. The PMMA/Graphene layers are transferred to a flexible substrate. Finally, the PMMA is dissolved by a solvent Martins et al. [53].

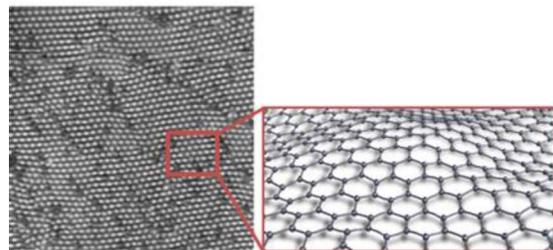


Figure 6. Scanning tunneling microscope (STM) image of a graphene sheet shows its hexagonal structure [54].

3.3. Zinc oxide (ZnO)

Recent studies of ZnO indicated a lot of interesting properties that make it durable for many applications. The wide bandgap of $\sim 3.4 \text{ eV}$, and the Young modulus of 64-144 GPa, make it applicable for flexible transistors and sensors [55, 56]. Furthermore, since doping ZnO was successfully doped, then both n-type and p-type semiconductors can be constructed. This led to the ability to fabricate not only transistors but also logic gates.

On the other hand, the most common method for growing ZnO on a flexible substrate is the inkjet printing method Ko et al. [57], physical vapor deposition (PVD) Kumar et al. [58], and hydrothermal Baruah and Dutta [59].

3.4. Organic semiconductors

Originally, organic materials, which are hydro-carbonic materials, have been used as an insulator in the microfabrication process. However, the

conductivity of the organic materials was successfully modified to be close to that of semiconductors and metals after exposure to bromine, iodine, or chlorine [48, 60]. This led to the invention of the conductive polymers. These polymers have interesting electrical, and optical, as well as their plastic and flexible, properties. Several research groups [61-63] used organic semiconductors in the design of F-FET as it is cheap and flexible. But the bottleneck is that it is relatively slow carrier mobility that makes the F-FET slow. However, growing single-crystal organic semiconductor Li et al. [64] improved the electron mobility with an average of $5.2 \pm 2.1 \text{ cm}^2/\text{Vs}$ compared to $1.5 \text{ cm}^2/\text{Vs}$ of the regular organic semiconductor. This made it comparable to the conventional semiconductor transistors. Fig. 7 displays flexible organic transistors.

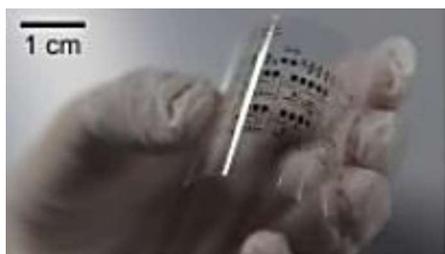


Figure 7. Photographic image of organic transistors [65]

4. Significant applications of flexible electronics

Recently, the trend toward rubber electronics has become significant due to the presence of many applications and the emergence of modern technologies. For example, in the medical field, a group of rubber sensors has appeared, which are used in the field of optogenetics, through which brain signals are read. This technology is considered one of the promising technologies that will open the door wide toward a new generation of medical devices. Energy scavenging is another application in the field of stretch electronics. This field includes the manufacture of stretchable RF antennas with their electronics in a flexible substrate. This antenna is called a patch antenna, which is a low-cost and simple structure. Such technology can be used in wearable devices that are used to collect energy from the environment. This technique probably going to be the building block for future powerless portable devices.

5. Conclusion

The progress in the F-FET to date is a result of work in multiple directions. These directions can be categorized into materials of a flexible substrate and the type of semiconductor. As for the semiconductor materials most research groups are currently working on nano and organic semiconductors. The field of flexibility seems to be promising due to its many potential applications, particularly in medical instruments and healthcare. This paper has attempted to summarize the fabrication methods and materials that probably help upcoming research to enter this field. Nano-flexible devices such as graphene, carbon nanotubes and nanoparticles seem to be candidates for future electronics as they have remarkable properties, particularly their electronic and mechanical properties.

Authors' contribution

All authors contributed equally to the preparation of this article.

Declaration of competing interest

The authors declare no conflicts of interest.

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