Review on Tunnel Field Effect Transistor For Biomedical Applications

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Abstract

The tunnel field effect transistor (TFET) is an emerging device showing potential use in many biomedical applications like pacemakers, cardiovascular defibrillators, hearing aid, analog cochlear processor, neural recording, retinal simulator, body area monitoring, etc. Bio-sensor which is used in biomedical applications is a chemical sensor which consists of biological identifying element and chemical to physical converting transducer. MOSFET can also be used in biomedical applications but it has the disadvantage of scaling effect. The advantage of using TFET is that it has lesser short channel effect because of its steep subthreshold characteristics and ambipolar nature. There are many types of TFET devices in which dielectrically modulated full gate and short FET devices are used in biosensing applications.

***Keywords: TFET, MOSFET, Biomedical Applications, Biosensors, Biomedical systems*.**

1. Introduction

MOSFET has played an important role in the emergence of the integrated circuits. The present-day Integrated circuits consist of millions of transistors due to the scaling capability of the metal oxide semiconductor field effect transistor transistors. The reduction in size of MOSFET reduced the power consumption of the Integrated Circuit and also the power dissipation of the Circuit [1]. Tunnel Field Effect Transistor which is invented by T. Baba in 1992 has many advantages over the MOSFET which are discussed below [2]

- Low power and low voltage applications.
- Subthreshold performance.
- Small leakage currents.
- High-speed switching
- Easier fabrication process as in MOSFET.
- Improved I_{OFF}/I_{ON} current ratio

Due to the above-mentioned parameters, tunnel FET is considered over MOSFET for high speed, low power, low short channel effects, reduced leakage current in many applications like Integrated circuits and biomedical applications. Tunnel FET transistors are based upon band to band tunneling effect that follows the charge-plasma concept, based on work function difference of the metallic gate contact and source/drain region along with silicon body thickness equal or less than the Debye length. The TFET due to its advantages can be used in various biomedical applications like

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pacemakers, hearing aid, retinal simulator, neural recording system and so on. The design of a biomedical device requires several blocks like energy subsystem, communication subsystem, ultra-low power signal processing, analog to digital converter, sensors and actuators [3]. The sensors used in the biomedical applications consist of a transducer for converting the chemical reactions to the physical actions [4].

2. Tunnel FET structures

There are many types of TFET like the feedback TFET, p-n-in TFET, NEMFET, raised buried oxide TFET, Junction less TFET, double gate TFET, vertical TFET, Doping less PNPN TFET.

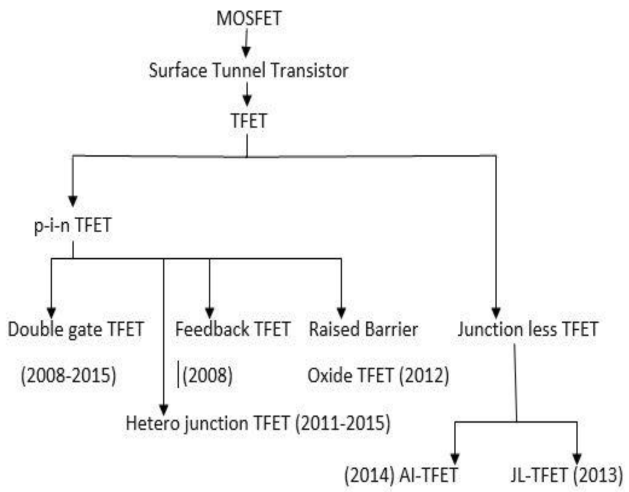

Fig 1 Evaluation of Tunnel Field Effect Transistor

Out of the available TFET, doping less PNPN TFET and the Vertical DG-TFET shows improved performance than the planner structures. The dielectrically modulated full gate and short gate TFET are used as the Biosensors. The Dielectrically modulated TFET is one of the best variant TFET based Biosensor for its capability to detect both charged as well as charge-neutral biological Species [5].
The characteristics of the tunnel FET, when compared to the conventional MOSFET (Fig.2), show an advantage of TFET over the MOSFET. The TFET is preferably used in biomedical applications over the MOSFET because of its high switching speed due to band-to-band tunneling of charge carriers with small increase of input voltage.

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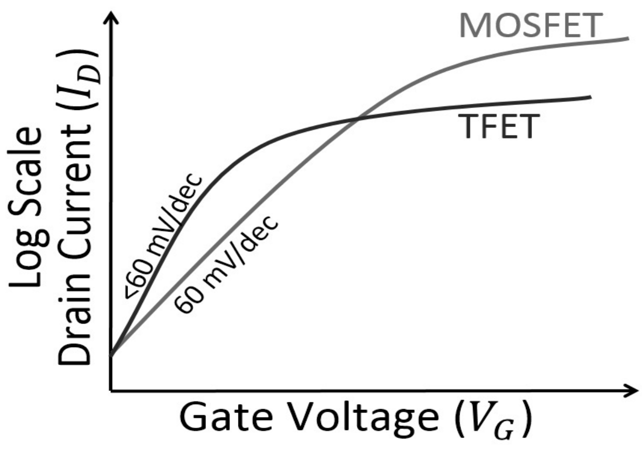

Fig 2. Comparison of TFET and MOSFET characteristics

Surface TFET:
Toshio Baba invented surface TFET which has the advantage of optimal performance even with gate lengths of 0.1μm. The surface tunnel transistor is fabricated using the GaAs or AlGaAs which can be used in biomedical applications.

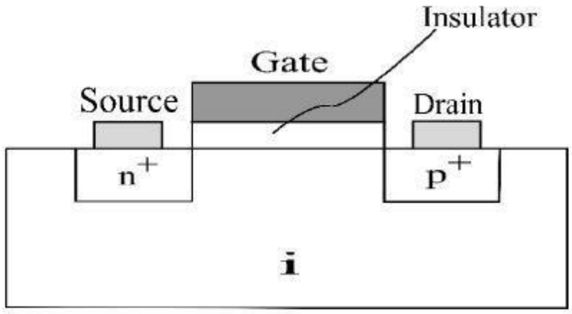

Fig 3. Surface Tunnel Transistor

Basic p-i-n Structure:
The pin structure is a heavily doped p-n diode which acts in reverse bias condition. Based on the gate voltage the TFET acts as a reverse bias p-n junction diode. If the p-i-n structure is fabricated with a thin gate, then there may be a problem of sharp swing.

Feedback FET:
Alvaro Padilla et al. invented the feedback FET which has a structure similar to that of the Lubistor designed to meet the required steep swing. However, this structure has some problems like voltage on forward and reverse voltage sweep is different and the voltage depends on the Drain voltage.

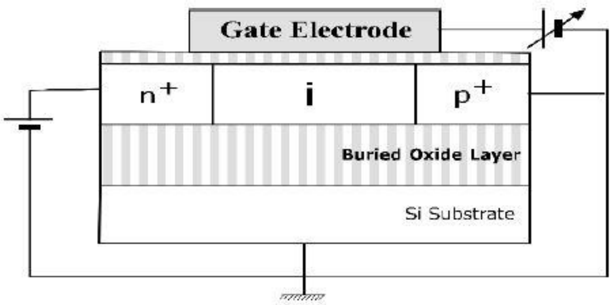

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Fig. 3 Device structure of TFET

p-n-i-n TFET:

Wei Cao proposed p-n-i-n structure which is basically a TFET with n-layer at the tunneling junction. The p-n-i-n structure faces the disadvantage of the reliability issue due to the tunneling effect at the junction. The change in the device process in a p-n-i-n structure may increase the sensitivity of the TFET.

Raised Buried oxide tunnel FET:

To cover the disadvantage of I_{on}, the raised buried oxide TFET is discovered. The raised buried oxide TFET has the advantages of I_{ON}(Maximum), I_{OFF}(Minimum), maximum I_{ON}/I_{OFF} ratio, minimum steep swing and reduced miller capacitance effect.

Junction less TFET:

The junction-less TFET has high electrical performance because it is a quantum mechanical device that is based on band-to-band tunneling. It has lower variability than MOSFET. It is widely used in biomedical applications because of its high tunneling current and low bandgap heterostructure channel. The asymmetric Junction less TFET is used in sub-10nm region.

Double-gate TFET:

In the DG-TFET the added gate to the normal TFET will increase the current. It contains the heavily doped p junction which helps to the tunnel of charge carriers. It has two gates namely the tunneling gate and the auxiliary gate. Due to the high current gain in Double gate tunnel FET, these are used in biomedical applications.

Dual-material DG-TFET:

Rajat Vishnoi proposed Dual-material DG-TFET with higher I_{ON} and I_{OFF} currents. It has a lower work function for tunneling gate than auxiliary gate in n-type TFET and has a higher work function for tunneling gate than auxiliary gate in p-type TFET. The triple metal DG-TFET is a type of DG-TFET which is made of three different work functions which increase the ON-current and decrease the OFF-current.

Vertical TFET:

The subthreshold swing is a very important parameter in upcoming days in TFET. The vertical TFET gives low subthreshold swing which results in high I_{ON}/I_{OFF} ratio. This is very much used in scaled devices which follows Moore's law. This device shows maximum efficiency in silicon-based devices.

Doping PNPN TFET:

The PNPN structure (Fig.4) has an extra n pocket when compared to the normal PNP TFET. A tunnel is formed between the p+ region and the n pocket which decreases the tunnel width and creates a local band bending. The Doping PNPN TFET has the advantages of better I_{ON}, tunneling rate compared to conventional TFET [5].

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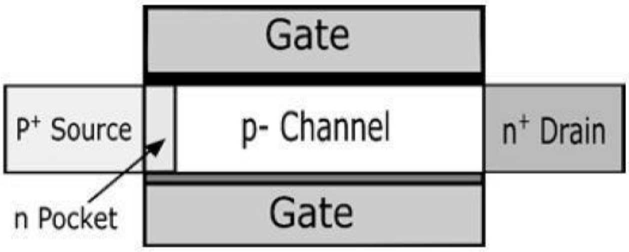

Fig. 4 PNPN Tunnel structure

SRG Tunnel FET:
The subthreshold swing plays an important role in tunnel FET. The TFET has better subthreshold swing when compared to that of the MOSFET and the band to band tunneling is also better in case tunnel FET, so TFET is widely used in biomedical applications. An SRG TFET is a type of TFET that offers good subthreshold swing and band to band tunneling, so it is used in heart and lung auscultation system, auscultation of pulmonary sounds and various applications using ECG [6].

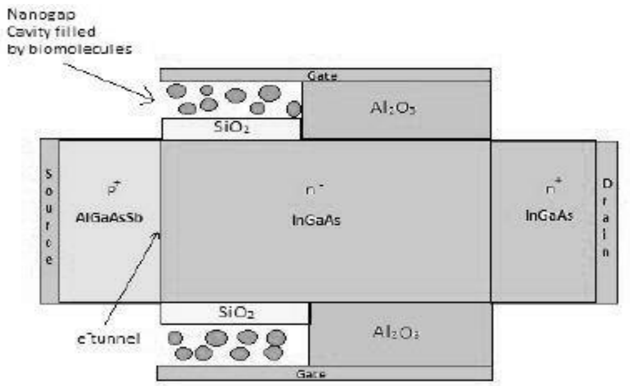

Fig 5. Structure of SRG Tunnel FET based biosensor

2.1 Electronics Biomedical systems

The basic biomedical systems mainly consist of actuators and sensors, energy subsystems, signal processing and communication. The energy subsystem of the electronics biomedical system consists of energy harvester, energy storage and voltage converter as shown in Fig 6.

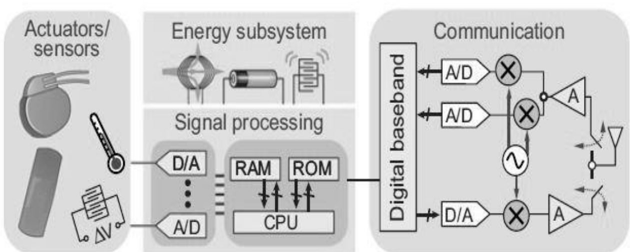

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Fig 6. Generic Biomedical Device

Energy Harvester:

For Non implanted systems the batteries can be replaced or they can be charged easily whereas in case of implanted systems the batteries cannot be removed without surgery. In such cases wireless electromagnetic transfer of energy is the best choice.

There are different energy harvesting options such as light, thermoelectric, vibration, near filed inductive energy transfer and the far-field electromagnetic energy transfer. The near and field are the wireless transfer of energy and are used in case of the implanted systems [3].

Energy Storage:

As we know that there are two major types of batteries, one is the primary battery which is non-rechargeable and the other is the second one which can be recharged. In implantable biomedical devices such as pacemakers the primary batteries are used [7]. The thin-film batteries which are the secondary batteries can be used in Non-Implantable biomedical devices.

Voltage Converter:

The voltage converter provides the biomedical device with required load voltage which can increase the life period of the biomedical device. Micropower switching converters which have a very high efficiency are very much used in the biomedical device [8].

Ultra-Low Power Signal Processing:

The types of operations involved in the biomedical device involve filtering, spectral analysis, correlation, modulation, threshold detection and data compression. Analog to digital signal converter is very important in any biomedical device as the signals acquired by the biosensors are in analog form [9].

Analog to Digital Converters:

The biomedical signals observed are in the form of analog form. These signals are analyzed by using the digital signal processors, so the analog to digital converter must be used in any biomedical device. A power efficient analog to digital converter must be chosen in the biomedical device in case the device is using a primary source of power [10].

Communication Transceivers:

The communication transceivers in a biomedical system support the communication between the different components present in the biomedical system. The communication between the components present in the biomedical system can be done through the wired connections whereas to make a communication with the external devices, the wireless connection may be needed. The wired communication has various disadvantages in biomedical devices so wireless communication is mostly preferred. For wireless communication, we can use the near field and far-field communication which works on electromagnetic waves [11].

2.2 Biosensors

The bio-signal acquisition is one of the important tasks in any biomedical application.

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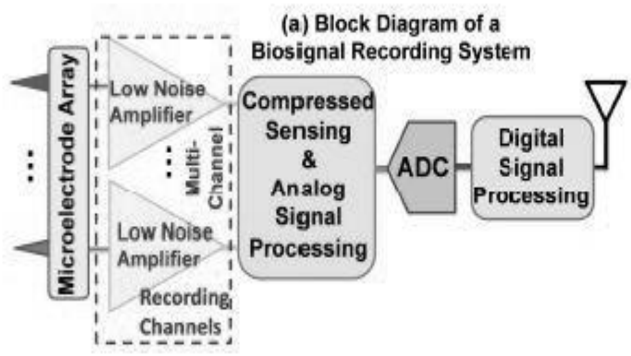

Fig 7 Block diagram of the multichannel bio-signal acquisition system

The block diagram of multichannel bio-signal acquisition system (Fig.7) consists of the electrode array for multichannel signal acquisition, analog front end for signal conditioning and a data processing unit. The biosensor is a transducer that converts the chemical reactions into the physical actions with the help of the chemical identifying element present in the Biosensor. There are several types of Biosensors available. They are Surface plasmon resonance (SPR) Biosensor, smart implantable biosensor, textile sensors, CNT based Biosensors, Enzyme-based biosensors and Integrated sensors [12].

SPR Biosensor:
Compared to many other Biosensors the SPR Biosensor has many advantages for characterizing molecular interactions. The BIACORE trademark is the most commercial instruments which are used to characterize the antibody and antigen (Fig.8) in the context of BIACORE [13].

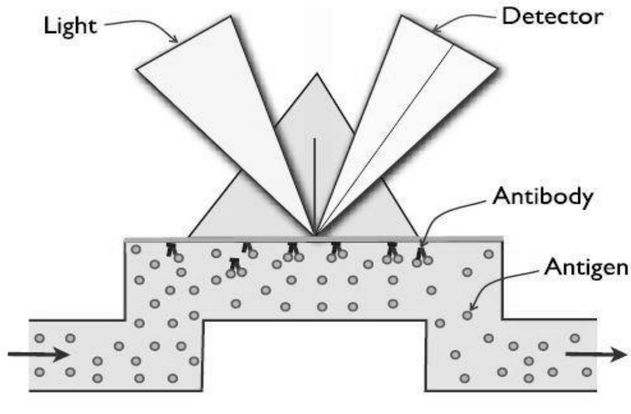

Fig 8. Typical biosensor assay

Smart Implantable Biosensor:
The single-walled CNT or the multi-walled CNT (Fig. 9) which are of micro or nano-size can be used to sense the analyte in smart implantable sensor. One disadvantage of the smart implantable biosensors is that their functioning is degraded with time [14].

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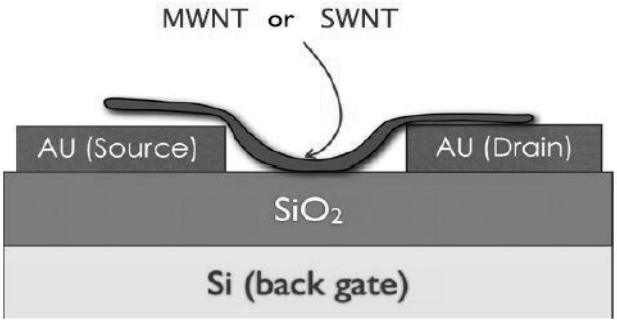

Fig 9. A cross-sectional view of the FET device

Textile Biosensor:
The highly durable and flexible can be constructed on textile sensors. The textile sensors are used in biotelemetry applications. Yarn based sensors of single and double wrapping methods are used to fabricate the yarn. The wearable health systems can be made on biomedical clothes which can be monitored through wireless transceivers [15].

Carbon nano-tube (CNT) based Sensor:
The CNT based biosensors are very much used in the fields of biomedical applications due to its properties of high aspect ratio, high mechanical strength, ultralight weight, high electrical conductivity and improved thermal conductivity. The multifunctional CNT (Fig.10) can be used in cancer therapy.

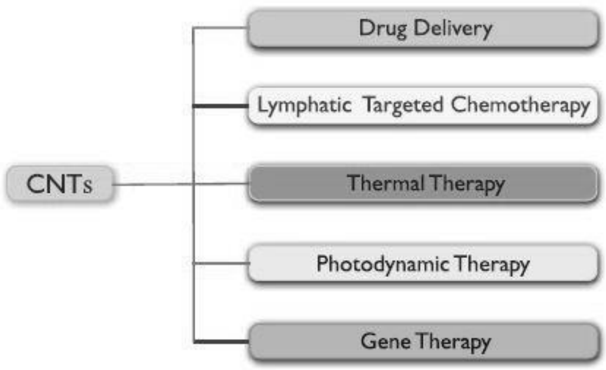

Fig. 10 Multifunctional carbon nanotubes in cancer therapy

Despite CNT sensor's advantages, it also has some disadvantages in which the toxicity is the major one which may cause skin irritation [16].

Enzyme Based Biosensor:
The two important bi-products of metabolism are urea and creatinine which can be easily detected by the potentiometric enzyme-based Biosensors. Amperometric Biosensor is a type of biosensor which response time, sensitivities and dynamic ranges like the potentiometric biosensors [17].

Integrated Sensors:

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The advanced lithography has increased the scope of integrated circuits which lead to the development of a wide variety of integrated sensors as shown in Fig 11. These integrated sensors are used in the blood flow measurement which is one of the most difficult measurements [19].

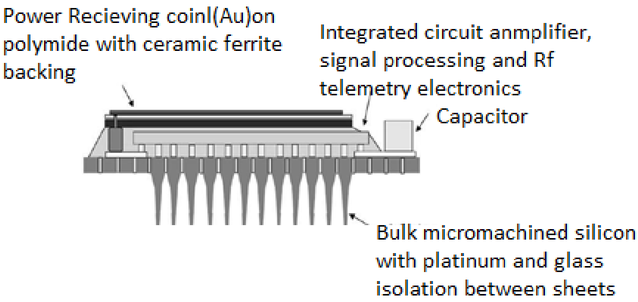

Fig 11. Complete integrated neural interface assembly

2.3 TFET for Neural Recording

The tunnel FET's are very much used in Biomedical applications like heart rate monitoring, neural recording, Hearing aid, Retinal simulation and so on. To use the TFET in the biomedical application, the amplifier is used in the design.
The double gate n-type HTFET and the p-type HTFET are shown in Fig.12 (a & (b) respectively that can be used to form a CMOS pair [19].

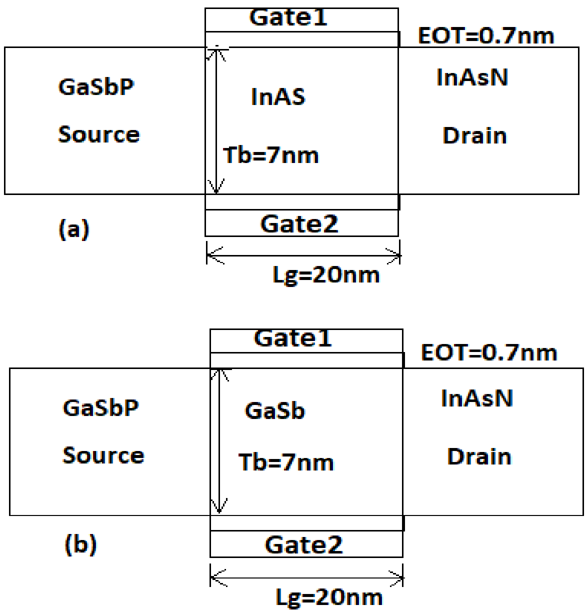

Fig 12 (a) N-HTFET and (b)P-HTFET

The HTFET is used neural recording applications because of its low operating voltage. The improved g_m/I_{ds} at low voltage and low I_{ds} provides different advantages such as enabling V_{dd} scaling to reduce the power consumption, reducing the NEF by reducing the thermal energy slope. To design the HTFET, we use the Verilog-A devices incorporated with the electrical noise model

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(Fig.13). The power noise trade-off is one of the parameters which limits the design of large-scale multichannel biosignal acquisition system.

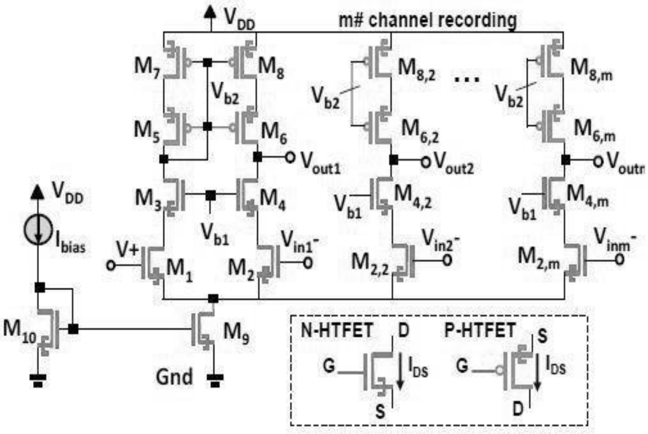

Fig 13 Telescopic OTA architecture with HTFET for multi-channel recording.

HTFET neural amplifier for multichannel bio-signal:
By using the capacitive feedback topology, closed loop HTFET is designed. We use the dc bias voltage to bias the common voltage of the input through the resistive divider network. A performance comparison of HTFET and FinFET is shown in table 1 on the basis of analog performance parameters.

Table 1 Performance comparison of HTFET and FinFET

	HTFET	**FinFET**
Technology	20nm HTFET	20nm Si FinFET
Bias Current	10nA	10nA
Supply Voltage	0.5V	1V
Power	5nW	10nW
Closed loop gain	39.4	28.1dB
Bandwidth	12Hz-2.1kHz(C_L=2pF)	4Hz-529Hz(C_L=2pF)

3. Conclusion

In this paper, several TFET structures have been compared in terms of their ON/OFF performance and their uses in the biomedical applications including different types of biosensors and biomedical

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devices. The advancement of technology has increased the usage of TFET devices in the biomedical applications. These TFET devices are used in the various biomedical applications like pacemakers, hearing aid, retinal simulators and neural recording systems. The biomedical applications include the latest technology like the double gate TFET and the hetero junction TFET.

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