# Nano-enabled Green Technologies for Electronics and Energy Applications

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## ABSTRACT

Green electronics is largely driven by performance limitations of scaled Si-based CMOS due to the exceptionally high power dissipation arising in such devices at nanoscale dimensions. Novel architectures for computation are currently in consideration, which include tunneling field-effect-transistors (TFETs), as well as nano-electro-mechanical-systems (NEMS) due to their abrupt ON/OFF transitions, low OFF state currents and high speed operation. Besides this overview of green transistor technologies, where low-dimensional materials such as graphene and semiconducting nanowires are under consideration, the other area that is discussed in this paper relates to the use of environmentally friendly, biodegradable organic polymers, for enabling high-efficiency, low-cost organic photovoltaics. Other advantages of organic PV lie in manufacturing processes that utilize room temperature techniques, where such solar cell architectures are also compatible with flexible electronics using roll-to-roll processing.

***Keywords***: green electronics, TFETS, NEMS, organic semiconductors, organic photovoltaics

## 1 INTRODUCTION

The pervasive use of computer systems, either in large information technology (IT) data centers or portable devices, is a leading contributor to global energy usage and the growing carbon footprint.[1] Analysis shows that efficient use of energy in the IT industry is expected to reduce green house gas emissions by 30% / year, which will amount to more than $300 billion in energy savings. In order to realize this saving, it is important to increase the efficiency of computer systems by developing low-power and energy-efficient green transistors for enabling green computing or green electronics.[2] The development of green electronics has the potential to reduce energy consumption and thus impacts the energy sector as shown by the schematic in Fig. 1. At the same time, it is also imperative to develop clean alternative energy sources since fossil fuel reserves are limited and lead to $CO_2$ emissions and global warming. The urgency for developing low-cost, high-efficiency, renewable energy sources is very pressing since worldwide demand for energy is expected to triple by the end of the century. Here we consider the use of organic materials which are environmentally friendly and biodegradable and present a potentially promising avenue for the realization of high efficiency, clean alternative energy sources at low cost. In this paper, an overview in the development of green electronics is presented in Section 2.0, and then in Section 3.0 the use of organic materials for energy harvesting is then discussed.

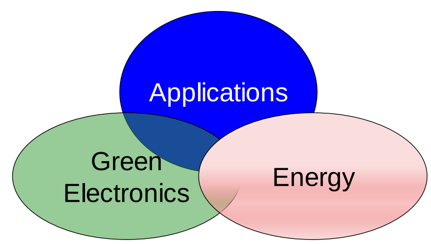


Figure 1: Schematic showing the intersection of green electronics with energy.

## 2 LOW-POWER ENERGY-EFFICIENT GREEN ELECTRONICS

Over the past several decades, scaling in semiconductor transistors has enabled enhancement in performance of complementary metal-oxide-semiconductor (CMOS) by increasing switching speed, density, functionality and cost. However, Si-based CMOS has been stretched to the point that further miniaturization will soon create performance limitations in these devices arising from high power consumption. New materials and technologies are thus vigorously being explored beyond Si, in order to overcome performance limitations from ultra-miniaturized Si-CMOS.[3] This paper presents an overview of two candidate technologies which are under consideration for enabling steep sub-threshold characteristic devices, specifically tunneling field-effect-transistors (TFETs),[4] and nano-electro-mechanical-systems (NEMS)[5] for the realization of low-power, energy-efficient green transistors. Section 2.1 and Section 2.2 provide an overview of TFETs and NEMS, respectively.

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## 2.1 Tunneling Field-Effect-Transistors

Green transistors should have the ability to operate at ultra-low supply voltages while providing enhanced or equivalent performance compared to conventional CMOS. While reducing the supply voltage in conventional CMOS is an effective means to reduce power dissipation, the ON/OFF ratios in these devices degrade due to increasing leakage currents. The non-abrupt switching characteristic in CMOS is responsible for this behavior and hence makes CMOS very energy inefficient, particularly at nanoscale dimensions. Thus the candidate technologies that exhibit more abrupt switching characteristics are highly desired. The sub-threshold swing is the primary metric used to capture the abruptness of this switching transition and quantitatively it is calculated to be 60 mV/decade for CMOS.[6,7] The value is essentially determined by the "thermionic emission" mechanism for carriers to be injected from the source to the channel region, as shown by the band diagram in Fig. 2a.

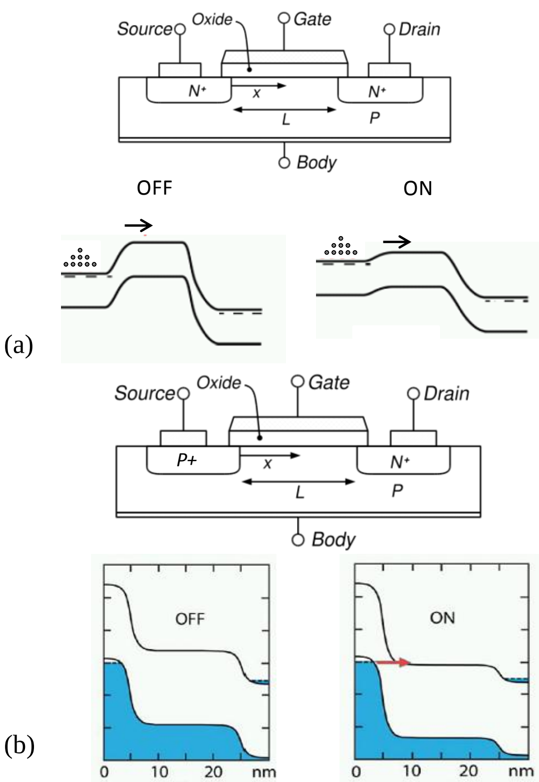
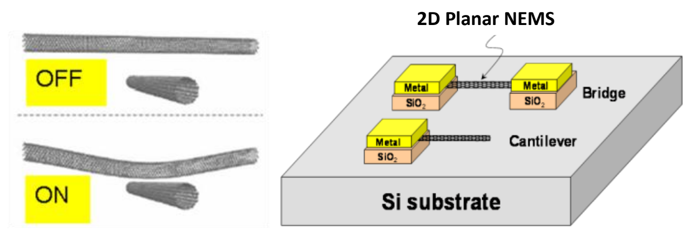



Figure 2. (a) Conventional CMOS transistor where turn-off is limited by thermionic emission. (b) In a TFET the current is determined by tunneling of electrons from the valence band in the source to the conduction band in the channel.

TFETs, on the other hand, have the potential to reduce the supply voltage to less than 0.5 V, and the ultra-fast switching transition leads to the potential for high frequency operation. The carriers are not thermally injected over a barrier unlike conventional CMOS (Fig. 2a), but rather the injection mechanism is based on interband tunneling, where charge carriers go from one energy band into another at a heavily doped p+–n+ junction as shown in Fig. 2b. The interband tunneling can be switched ON and OFF abruptly by adjusting the band bending in the channel by applying a gate voltage. The main challenge with TFETs is to increase the ON state current to the level of CMOS, by enhancing the band-to-band tunneling probability. Various material systems have been attempted for realizing TFETs including semiconducting heterostructure nanowires,[8] carbon nanotubes and graphene, where a sub-threshold swing < 60 mV per decade (~ 40 mV per decade) has been achieved.[9]

## 2.2 Nano-electro-mechanical-systems (NEMS)

NEMS are another class of devices which have the potential to enable low-power, energy efficient, green switching devices that exhibit abrupt switching transitions with steep sub threshold characteristics. The mechanical construct of NEMS devices, as elucidated from Fig. 3a, indicates that they offer near zero leakage characteristics.[10] In particular, carbon-based NEMS offer the potential for ultra-high switching speeds due to their ultra-high elastic modulus (> 1TPa).




(a) (b)

Figure 3. (a) The ON and OFF states in NEMS are physically isolated which reduces the OFF state currents. (b) The bridge and cantilever architectures have been commonly explored for 2D planar NEMS.

NEMS devices also have the potential to operate in high temperature and highly radiating environments. Shown in Fig. 3b are two commonly explored 2D planar NEMS architectures, the bridge and cantilever. The challenges with NEMS lie in reducing the pull-in voltage and to increase the low ON-state current. In addition, the reliability of such devices also needs to be increased by eliminating stiction issues that are commonly seen in these devices.

# 3 ORGANIC MATERIALS FOR GREEN ELECTRONICS & ORGANIC PV

Research in organic semiconductors has progressed to the point that commercial applications have been realized in areas such as organic light emitting diodes (OLEDs) for solid state lighting and displays, as well as organic field effect transistors (OFETs) for RFIDs, e-paper and flexible electronics. The use of organic semiconductors for photovoltaics (PV) has also seen tremendous progress over the past decade with power conversion efficiencies (PCE) that have risen from 1% to above 10.6%. Organic PV (OPV) provides advantages in its very low-cost manufacturing processes that utilize room temperature techniques, unlike crystalline Si and other inorganic PV technologies that are not cost-effective. Other advantages of OPV include the use of environmentally friendly materials, and compatibility with roll-to-roll processing for the realization of solar cells in a flexible and conformable platform. In Section 3.1 the application of organic semiconductors for green electronics, specifically OFETS and OLEDs is described, which is followed in Section 3.2 with a description of the application of organic semiconductors for OPV.

## 3.1 OFETs and OLEDs

Tremendous progress has been made in recent years that has enabled organic semiconductors to serve as effective light emitters in organic light emitting diodes (OLEDs),[11] logic and memory elements using organic field effect transistors (OFETs),[12] as well as photodetectors. As an example, in Fig. 4a an OFET is shown, where source-drain currents are modulated in the organic semiconductor through the application of a gate voltage. Such devices have applications in flexible electronics (Fig. 4b) or for e-paper and smart textiles.

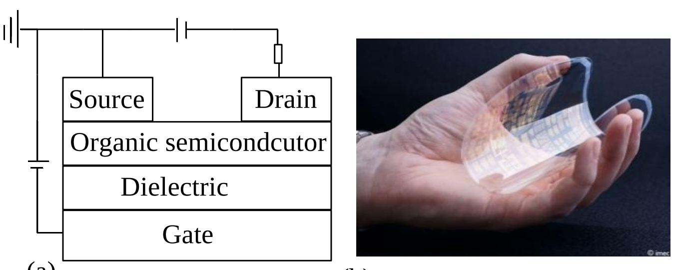



Figure 4. Organic semiconductors used in (a) OFETs which has applications in (b) flexible circuits in RFIDs, e-paper and memory.

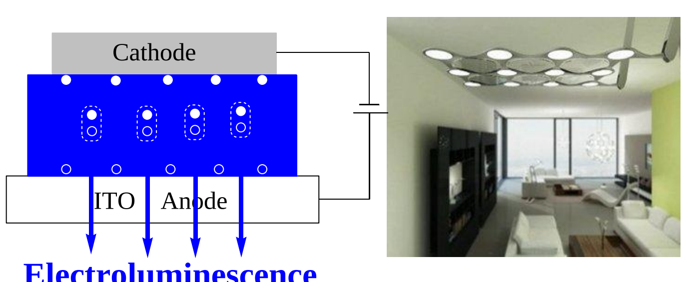



Figure 5. Organic semiconductors used in (a) OLEDs which have applications in (b) solid state lighting and displays.

In the OLED device architecture (Fig. 5a), applying a voltage between the transparent anode and metallic cathode injects charge carriers from both electrodes within the organic semiconductor in the trilayer structure. These injected electrons and holes then create excitons which then emit light upon recombination at a wavelength that is determined by the choice of the active layer. The tremendous success in OLEDs has enabled commercial products from such devices in ultra-thin, full color, flat panel displays, as well as for solid state lighting (Fig. 5b).

## 3.2 Organic Photo-voltaics

The working principle in an OPV device is outlined in Fig. 6a, where a photon from incoming light is absorbed and results in the formation of electron-hole pairs that generate bound excitons in the organic active layer. These excitons are then separated and collected as charges at the terminals, where they generate a photocurrent.[13] This is in contrast to an inorganic semiconductor,[14] where the absorption of a photon leads directly to the creation of free electrons and holes which are then driven away to the respective electrodes through the built-in potential. In current generation organic solar cells, the composite active layer can be prepared on large area substrates using techniques such as spin-coating, inkjet-printing, spray coating, gravure-coating, which are also compatible with roll-to-roll processing as shown in Fig 6b.

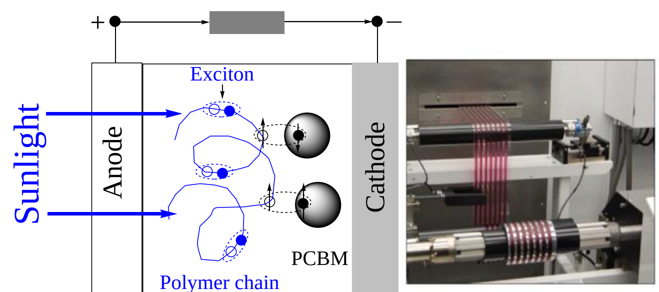



Figure 6. a) Working principle of an organic solar cell. (b) Roll-to-roll processing can be used to create OPV cells.

While crystalline silicon based PV cells and other inorganic materials such as CdTe and copper-indium/gallium-selenide/sulphide $Cu(In,Ga)Se_2$ (CIGS) account for 99% of the world production of solar cells, the need for high-temperature processing and high vacuum environments keeps the cost of these modules high. The urgency for developing low-cost efficient renewable energies is even more pressing considering the demand arising from emerging economies, such as China, India and Brazil. In order to meet the DOE cost goal for achieving $0.2/Watt, low cost, high efficiency PV technologies are actively being sought and includes the exploration of low-cost, environmentally friendly organic materials.

Figure 7 surveys the various technologies that are currently in consideration for PV, from crystalline Si cells, multi-junction concentrators, thin-film technologies to emerging technologies which involves the use of nanomaterials, and also includes organic PV technologies.

The PCEs in crystalline Si have reached ~ 25% and second generation technologies have also been developed that are based on thin films (amorphous Si, CdTe, and CIGS). While CIGS thin films have PCEs ~ 19 %, amorphous Si, although being cheaper than crystalline Si, has lower efficiencies ~ 12% and also suffers from stability issues which has limited its use in commercial applications.

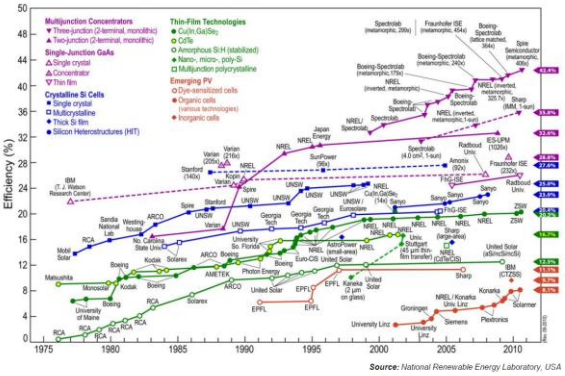



Figure 7. Comparison of OPV to other energy harvesting technologies. Source NREL.

A wide variety of new organic materials have now emerged[15] which include conjugated p-type polymers such as regioregular poly(3-hexylthiophene) (P3HT) as the electron donors materials and fullerene derivatives, such as [6,6]-phenyl-C61-butyric acid methyl ester (PC61BM) or [6,6]-phenyl-C71-butyric acid methyl ester (PC71BM) as the n-type acceptors. Considerable progress has been made in enhancing the PCE in OPV from less than 1% in the poly(phenylene vinylene) (PPV) system to 4–5% in the poly(3-hexylthiphene) (P3HT) system, to 10.6% achieved recently.[16] The significant progress seen in PCE in OPV can also be elucidated by the steeper slope of the OPV technology line in Fig. 7 in recent years, when compared to other energy harvesting technologies that have remained largely flat during the past 10 – 15 years, such as CIGS and amorphous Si. Despite the progress, challenges still lie ahead in improving PCE's in OPV further to make them economically competitive with other commercial technologies, as well as enhancing their operational stability.

In conclusion, in this paper an overview of green electronics was presented, with a focus on TFETs as well as NEMs. The second section focused on the use of organic semiconductors for OFETs, OLEDs with a particular emphasis on OPV.

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## REFERENCES

1 The Climate Group. "SMART 2020: Enabling the low carbon economy in the information age," Technical report, The Climate Group, 2008.

2 C. Hu, "Prospect of Tunneling Green Transistor for 0.1V CMOS," *IEDM Tech. Digest*, 16.1.1 (2010).

3 K. Bernstein, R. Cavin, W. Porod, A. Seabaugh, and J. Welser, "Device and architecture outlook beyond CMOS switches," *Proc. IEEE* **98**, 2169 (2010).

4 A. Ionescu and H. Riel, "Tunnel field-effect transistors as energy-efficient electronic switches," *Nature* **479**, 329 (2011).

5 K. L. Ekinci and M. L. Roukes, "Nanoelectromechanical systems," *Review of Scientific Instruments* **76** , 061101 (2005).

6 W. Y. Choi, B.-G. Park, J. D. Lee and T.-J. K. Liu, "Tunneling Field-Effect Transistors (TFETs) with sub-threshold swing (SS) less than 60 mV/dec," *IEEE Electron Dev. Lett.* **28**, 743 (2007).

7 A. Seabaugh and Q. Zhang, "Low-voltage tunnel transistors for beyond CMOS Logic," *Proc. IEEE* **98**, 2095 (2010).

8 K. Tomioka, "Tunnel field-effect transistor using InAs nanowire/Si heterojunction," *Appl. Phys. Lett.* **98**, 083114, (2011).

9 J. Appenzeller, Y.-M Lin, J. Knoch and P. Avouris, "Band-to-band tunneling in carbon nanotube field-effect transistors," *Phys. Rev. Lett.* **93,** 196805 (2004).

10 T. Rueckes, K. Kim, E. Joselevich, G. Y. Tseng, C. L. Cheung, and C. M. Lieber, "Carbon Nanotube-Based Nonvolatile Random Access Memory for Molecular Computing", *Science* **289**, 94 (2000).

11 S. Reinke, F. Lindner, G. Schwartz, N. Seidler, K. Walzer, B. Lussem, and K. Leo, "White organic light-emitting diodes with fluorescent tube efficiency," *Nature* **459**, 234 (2009).

12 D. Gundlach, "Low power, high impact," *Nature Materials* 6, 173 (2007).

13 G. Yu, J. Gao, J. C. Hummelen, F. Wudl, A. J. Heeger, "Polymer photovoltaic cells – enhanced efficiencies via a network of internal donor-acceptor heterojunctions," *Science* **270**, 1789 (1995).

14 D. M. Chapin, C. S. Fuller, G. L. Pearson, "A new silicon p-n junction photocell for converting solar radiation into electrical power," *J. Appl. Phys.* **25**, 676 (1954).

15 C. Bardeen, "Exciton quenching and migration in single conjugated polymers," *Science* **331**, 544 (2011).

16 G. Li, R. Zhu and Y. Yang, "Polymer solar cells," *Nature Photonics* **6**, 153 (2012).