Organic Electronics: Enabling Monolithic Integration On 'ANY' Substrate

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Organic Electronics is a new branch of electronics where organic materials instead of traditional inorganic elements such as Silicon or germanium are used for making transistors, solar cells, light emitting diodes and other elements. In order to appreciate the benefits offered by this new technology, it is important to understand the history of electronics and how it has transformed our lives. This is briefly described in section-1. The limitations of traditional electronics are discussed in section -2 and the advantages of organic electronics are summarized in section-3.

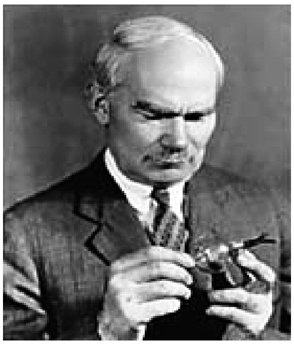
1. Evolution of Electronics

Electronics has revolutionized almost all aspects of our lives. The reason for this can be appreciated in terms of following three statements:

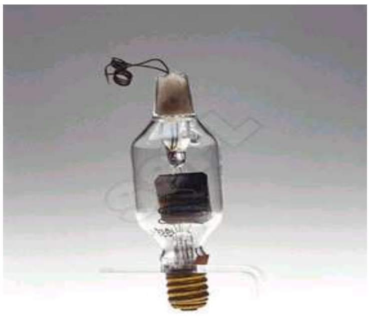
1. Every action or activity requires energy
2. Electricity is one of the most useful forms of energy (it is 'easy' to generate, 'easy' to transport over long distances and can be 'easily' converted into other forms of energy)
3. Electricity can be very precisely controlled using tools and techniques provided by Electronics

Suppose we have a form of energy and we can make it do 'whatever' we want . Our Imagination then is the only limitation in terms of what we can do and it is not surprising then that control of electricity ushered in the Electronics revolution.

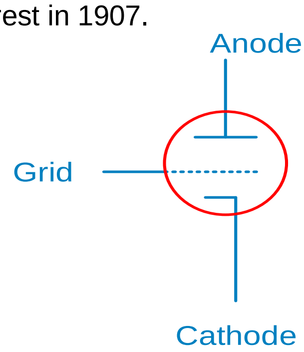
This revolution began with the invention of Triode by Lee De Forest in 1907.



Lee De Forest



Triode



Schematic diagram of a Triode

The triode is a vacuum tube with three electrodes namely Anode, Cathode and Grid. When cathode is heated, it emits electrons through a process called Thermionic Emission. A positive voltage applied to the Anode attracts the electrons to the anode causing a current to flow between anode and cathode. Application of a negative grid voltage causes number of electrons reaching anode to decrease thereby allowing gird voltage to control anode current. Triode exhibits a very importance characteristics namely transconductance. The ratio of current and voltage or change in current with voltage is called conductance. When both current and voltage are across the same pair of terminals, we call it simply conductance or sometimes input conductance if the pair of terminals are where input is applied or output conductance if output is taken across them. When current and voltage across two different pairs of terminals are taken, then the ratio is called transconductance. Any device with three or more terminals will exhibit transconductance but what was special about triode was that transconductance was much greater than output conductance

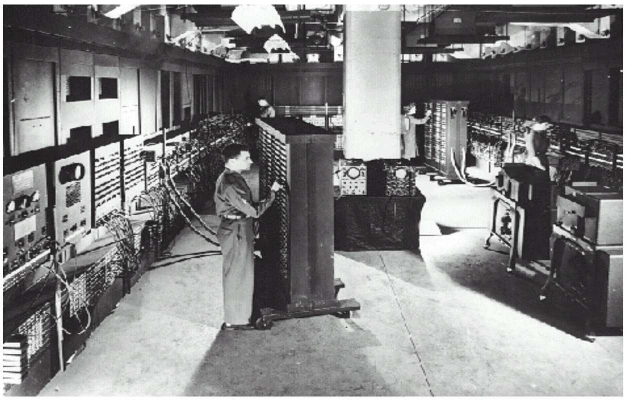
$$\frac{\partial I_A}{\partial V_G} >> \frac{\partial I_A}{\partial V_A} \qquad (1)$$

In other words, the anode current I_A was much more sensitive to grid voltage V_G rather than anode voltage V_A. This is a very surprising property because normally one would expect current flowing between a pair of terminals to be very sensitive to voltage applied across it and much less sensitive to voltage applied across a different pair of terminals. Triode was the first device to exhibit the unique property of prominent transconductance. Equation 1 also implies that a small change in grid voltage can cause a much larger change in anode voltage

$$\Rightarrow \frac{\partial V_A}{\partial V_G} >> 1 \qquad (2)$$

In other words, Triode was capable of amplifying electrical signals. The invention of the Triode had the immediate consequence of revolutionizing communication by allowing long distance Telephony and wireless radio communication. Telephone had been invented earlier but communication distance was limited because the electrical signal got weaker as it propagated over the wire and eventually became indistinguishable from the background noise. Invention of amplifiers allowed signal to be amplified and re-transmitted before it became weak thereby allowing signal transmission over long distances. Wireless radio communication also required amplifiers for several reasons including the fact that the received signal is very weak and useless unless amplified. Transmission of signals also requires their frequency to be shifted to higher values which requires oscillators built using amplifiers with positive feedback.

Using a triode one can also build a digital inverter where a low input voltage applied to the grid results in a high anode voltage and vice versa. Two triodes can be combined to create a two input NOR gate which being a universal gate can be used a create any logic function including addition, subtraction , multiplication etc. Two Triode tubes can also be cross coupled to create a latch which is a memory. Thus, we see that the triode had the capability to revolutionize information processing and storage as well. Although the triode had within it the seeds of information revolution , it was difficult to harness it. The number of vacuum tubes that could be integrated to create a circuit was very limited which can be appreciated through the example of an early electronic computer called Electronic Numerical Integrator and Computer (ENIAC). It was a revolutionary computing machine with speed more than hundred times higher than any other computing machine of the time. ENIAC was an electronic circuit consisting of 17,468 vacuum tubes, along with about 70,000 resistors and 10,000 capacitors. It occupied a 30 x 50 feet room, weighed about 30 tons and consumed hundreds of kilowatts of power.



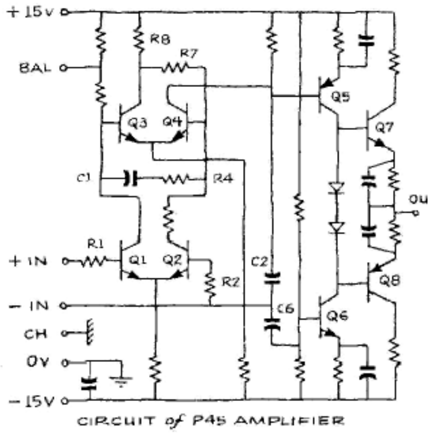
ENIAC Computer

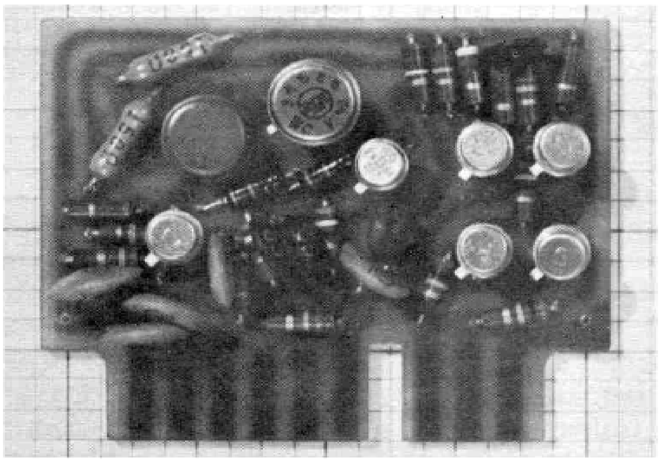
Sharp CS-10A Calculator

Reliability of the circuit was poor with an average of about 50 tubes needing replacement each day. Thus, although triode (and other improved vacuum tubes) had very important characteristics that enabled it in principle to perform important functions, in practice it was difficult to integrate large number of these tubes to create useful systems. In other words, the **integration level** was limited.

The next momentous event in the history of electronics was the invention of transistor in 1948 by Bardeen, Brattain and Shockley at Bell laboratories. A transistor was a three terminal device that like triode exhibited transconductance much larger than output conductance. It could amplify and do most of what a triode could do but was much smaller, consumed much less power and was also far more reliable. As a result, the ability to integrate more devices and make complex circuits increased tremendously. A computing machine that occupied an entire room could now fit on a table. Although integration level increased significantly, it was still limited which can be appreciated through the example of Sharp CS-10A calculator which debuted in 1964. It contained 530 germanium transistors, 2300 diode, measured 420 x 440 x 250 mm ,weighed 25Kg and consumed 90 Watts of power!

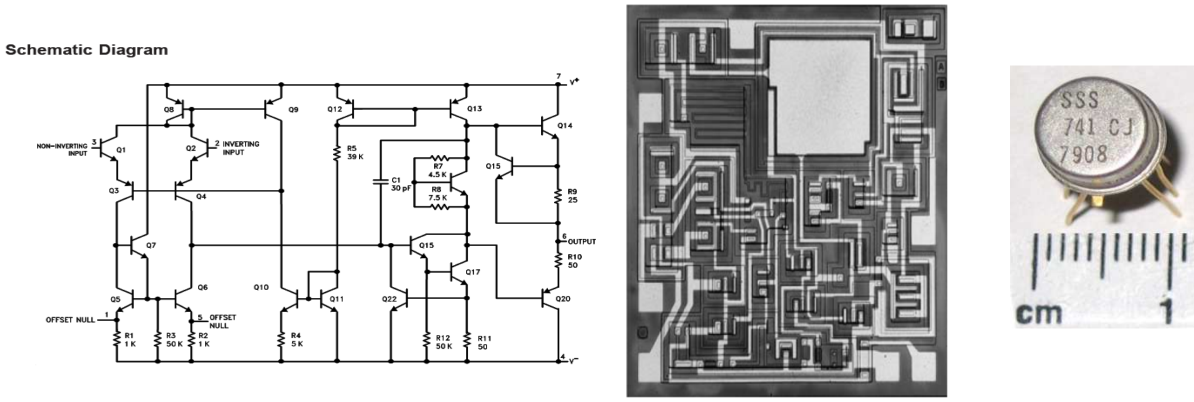
The invention of transistor was a necessary step but not sufficient by itself for Electronics revolution. None of the electronic products that we are familiar with such as cell phones, laptops, pacemakers etc would be possible without the invention of Integrated Circuits (IC) in 1958 by Rober Noyce from Fairchild and Jack Kilby from Texas Instrument. Prior to this invention, circuits were made by assembling discrete components (transistors, resistors, capacitors etc) on an insulating substrate. The next figure shows a discrete operational amplifier (opamp). Because the components had to held either in hand or by a machine during the assembly process, its size had to be of the order of a centimeter. Thus, even though a transistor is much smaller with size in microns, it has to be packaged so that it became sufficiently large sized to be held and manipulated.





P45, an early operational amplifier built using discrete transistors

Components with size in centimeters implies that a circuit with a few thousand components would have a length scale of the order of a meter! Since package makes the transistor orders of magnitude heavier, the resulting circuit would also weigh significantly. The invention of IC represented a revolution in fabrication of circuits in which all the components and the wires interconnecting them were made on the same semiconducting substrate. Only the final integrated circuit had to be packaged to be subsequently used in larger systems. Thus, a circuit consisting of thousands of components has a size which is almost the same as a single packaged transistor. Figure below shows the schematic of famous 741 opamp, its chip layout and its size.



741 opamp (a) circuit schematic, (b) chip layout , (c) packaged IC

All the 22 transistors (P and N-types), 12 resistors and a capacitor and the wires interconnecting them are made on silicon substrate and the packaged opamp shown above on the right measures and weighs almost same as a single transistor !. The invention of IC unleashed the power inherent in a transistor and circuits with increasing integration level could be fabricated. There appeared to be no conceptual bottlenecks to integration level of the circuit and a new era of integrated circuits began whose impact has been felt in all walks of life. Gordon Moore in 1965 predicted that integration level of circuits would double every two years or so, a trend that has continued to this day. The invention of integrated circuit was aptly recognized with Nobel Prize in the year 2000.

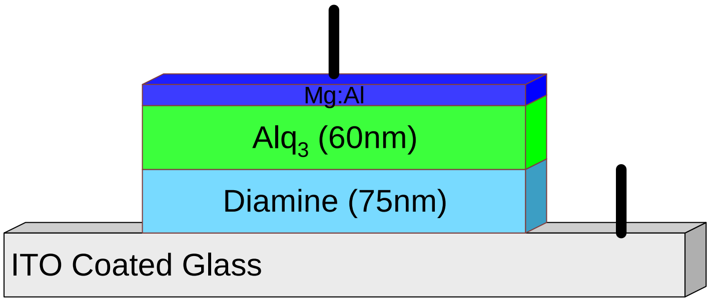
2. Limitations Of Conventional Inorganic Semiconductor Based Electronics

The brief discussion of history of electronics described above emphasized the importance of integration level of the circuits and use of **monolithic integration** to achieve large scale integration. However, conventional electronics based on inorganic semiconductors such as Silicon, Gallium Arsenide etc has the limitation that it precludes monolithic integration of transistors and other components on substrates such as glass, plastic etc. The reasons for this is that traditional electronics requires a crystalline semiconductor layer and uses processing steps such as oxidation, diffusion etc which require temperatures exceeding melting points of glass and plastic. The starting substrate for a silicon bipolar junction transistor (BJT) or a metal oxide field effect transistor (MOSFET) is a crystalline silicon wafer. A few defects and dislocations disrupting the crystalline symmetry can make the whole device non-functional. Silicon deposited on glass or plastic is amorphous (in other words disordered) in nature and has properties very different from crystalline silicon. Red light emitting diodes (LED) require a crystalline gallium arsenide (GaAs) wafer for fabrication and are very sensitive to defects in the material. LEDs made on GaAs deposited on glass or plastic will simply not work due to its amorphous nature. An optoelectronic integrated circuit with GaAs LEDs and Silicon transistors is also not possible because crystalline GaAs is difficult if not impossible to grow on Silicon and vice-versa due to their different lattice constants. These examples illustrate the constraints on monolithic integration imposed due to requirements of crystalline nature of semiconductor in traditional electronics.

To appreciate why monolithic integration on other substrates such as glass or plastic is of importance , consider the example of electronic displays. To make a display, one requires a two dimensional array of pixels or light elements of three primary colors (Red, green and blue) which can be switched on or off depending on the nature of image to be displayed. Although inorganic LEDs were invented in early 1960s, a display with reasonable resolution employing LEDs does not exist. The displays used in cell phones, laptops and TVs use liquid crystal displays (LCD) instead. LEDs are primarily used as individual light sources in most applications including the so called LED laptops and TVs where they have recently replaced the fluorescent backlight lamps. The reason for this is that a red LED and a blue or green LED require different semiconducting materials each of which must be crystalline. A GaAs substrate allows red LED to be fabricated but gallium nitride (GaN) semiconductor required for blue LED is incompatible with gallium arsenide substrate. Thus both LEDs cannot be made on a common semiconducting substrate. Further, the semiconducting substrate is several times more expensive than glass making it economically unviable even if it were technically feasible to make LEDs of all three colors on a common substrate. It was mentioned earlier that none of the LEDs would work if semiconductors were deposited on glass because of their resulting amorphous nature. One might wonder why we cannot make red, green and blue LEDs separately and then integrate them on inexpensive glass. This would be integration of discrete components rather than monolithic integration where components are fabricated on the glass itself. One reason why this cannot be done is limitations in resolution of display that can be attained. As an example, consider a 2.4 inch diagonal cell phone color display with a 320 x 240 pixel resolution. A simple calculation shows that this requires about a 1000 pixels to be accommodated in a space of 5cm which is impossible considering that a single discrete component has a length scale of several millimeters. Further, the cost of display built using discrete LEDs would be prohibitive considering in mind the display requires almost a quarter of million LEDs to be integrated. This example illustrates that **monolithic integration on glass** is essential to make electronic displays of sufficient resolution and sufficiently low cost to be economically viable. The main drawback of conventional electronics then is that it restricts monolithic integration of components to a crystalline semiconductor and precludes usage of other substrates such as glass, plastic, fabric etc. The result is that electronic products often exist as standalone objects which hinders their seamless integration into our everyday life.

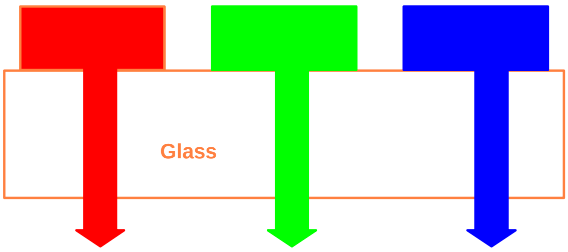
3. Key Advantages Of Organic Electronics

Organic semiconductors promise to **liberate** electronics by allowing monolithic integration of circuits on a wide variety of substrates such as glass, plastic , fabric and even simple paper. It has the potential to allow intelligence in the form of electronics to be embedded in our ambient in such a way that it is unobtrusive and integral part of the surroundings. This advantage comes from the fact that viable semiconductor devices such as transistors, LEDs, solar cells etc can be made using organic semiconductors that are amorphous in nature. Since there is no necessary requirement for organic semiconductors to be crystalline, they can be deposited on virtually ‘any’ substrate to make functional devices and circuits. Consider an organic LED for example shown below.



Schematic of an Organic Light emitting diode

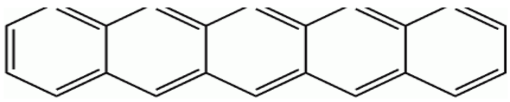
The LED is fabricated on glass which is coated with a conducting oxide called Indium Tin Oxide (ITO). This layer acts as the anode. Two organic semiconductors , one belonging to diamine family and the other Aluminum Tris(8-Hydroxyquinoline) (Alq_3) are next deposited on ITO coated glass. These semiconductors are deposited by simply vaporizing organic compounds in vacuum with the ITO coated glass substrate held close to it. Temperatures in the range 200-300^{o}C are often enough to vaporize these compounds since molecules are held together by weak Van der Waals forces. Compare this with temperature exceeding thousand degrees needed to vaporize silicon due to strong covalent bonds prevalent in the lattice. Cathode metal is next evaporated onto the substrate to complete the device fabrication. This method of fabrication is much simpler and uses low temperature processing steps only as compared to processes used to fabricate an inorganic LED. The organic LED shown above emits green light when a positive bias is applied between anode and cathode. Even though organic semiconductors are amorphous in nature, very efficient light emission is nevertheless obtained. If a red LED has to be made, a different set of organic semiconductors can be deposited adjacent to the green LED on the same glass substrate. Using metal masks, one can ensure that materials appropriate for a particular LED are deposited only at selected places. In this manner, it is relatively easy to fabricate red, green and blue LEDs side by side as shown below



Monolithically Integrated Red, Green and Blue Organic LED on Glass

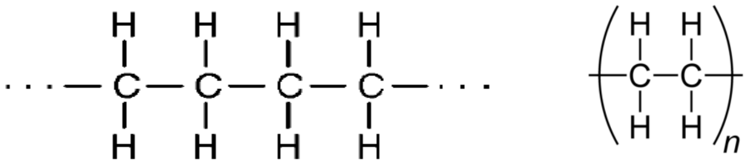
Monolithic integration of LEDs of different colors on glass is thus possible because organic semiconductors can be amorphous in nature and still emit light. Thus, where inorganic LEDs failed, full color displays with organic LEDs have been demonstrated and commercialized by several companies such as Kodak, LG and Samsung.

Organic semiconductors can be classified into two broad categories namely small molecule and polymers. Small molecule semiconductors as their name indicates have relatively smaller molecular weight. Pentacene with five fused benzene rings is a good example.



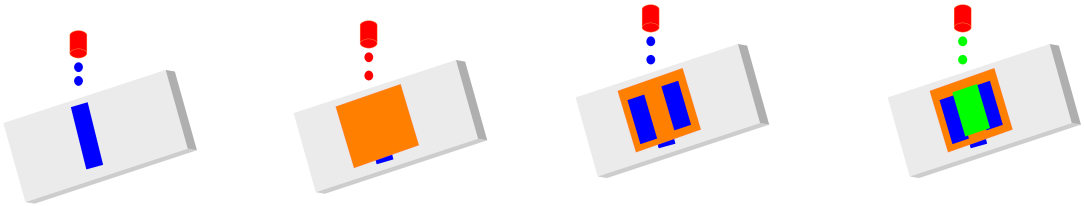
Structure of a Pentacene Molecule

The small molecule organic compounds are often insoluble in common organic solvents and thin films of these semiconductors are deposited by thermal evaporation as explained earlier. Polymers, on the other hand are giant macromolecules where a simple chemical unit is repeated large number of times as illustrated below



Polyethylene and its compact representation

Most semiconducting polymers are soluble in common organic solvents such as Chlorobenzene or xylene which allows for very simple fabrication process for devices based on them. One simple technique is spin coating where a few drops of solvent containing the polymer is dropped onto the glass plate and spun at speeds of around a 1000 RPM (revolutions per minute) for a minute or so allowing deposition of very thin films with thicknesses in nanometers. The solvent containing the polymer with some modifications can be converted into an ink which can then be used with an ink-jet process to print polymer semiconductors and polymer insulators as well. There are conducting polymers also so that one can print insulators, semiconductors as well as conductors thereby allowing devices such as OLEDs, Organic solar cells, organic thin film field effect transistors (OTFTs) and circuits based on them to be fabricated on plastic substrate in a manner similar to the way newspapers are printed !. The next figure illustrates how an OTFT may be fabricated using printing



Schematic illustrating fabrication of a transistor using Printing

Prototypes of OLEDs, solar cells and OTFT based circuits using different printing techniques such as ink-jet and gravure have already been demonstrated on flexible plastic sheets. The high throughput printing technology promises to significantly lower the cost of organic electronics based products in comparison to conventional semiconductor fabrication technology.

To summarize, by enabling monolithic integration on 'any substrate' and low cost roll-to-roll processing, Organic electronics holds the promise of **"Electronics Everywhere and for Everyone"**

(EE611, organic electronics course offered by dept. of EE at IIT Kanpur provides students with a broad background in the area. It covers all important aspects of organic semiconductor physics including electronic structure, luminescence and absorption of light, injection and transport of carriers. Operation, physics and modeling of three prominent organic semiconductor devices namely thin film transistors, light emitting diodes and solar cells are dealt in detail. The course is associated with a laboratory where students get an opportunity to fabricate and characterize transistors and solar cells. An undergraduate course on semiconductor devices is a prerequisite for the course.)