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Origin of Electronics

Electronics is a subject cultivated at different academic levels of undergraduate and postgraduate science and engineering curriculum. Beyond the classes, it has diversified applications in modern science, technology, economy, society, and daily life. The development of electronics throughout the last century may be treated as a distinct step along the progress of human civilization. This chapter sketches a brief outline of the background, evolution, and widespread applications of electronics. This also introduces the arrangement and relevance of topics in this book.

1.1 What Is Electronics

It is understood from our everyday experience that electronics is somehow related to the use of electricity. However, electricity is found in nature also, whereas electronic devices and the use of electricity in those devices are totally man-made. The techniques of electronic devices established several novel aspects in the use of electricity, which were never experienced earlier. Some salient features of electronics are mentioned in the following section.

- *Electrical Power Amplification*: An electronic device, such as a transistor can be made to amplify voltage and current simultaneously that cannot be achieved with other electrical gadgets, such as a transformer.
- *Nonlinear Current–Voltage Relationship*: According to Ohm's law, the steady current through a resistor, capacitor, or inductor varies linearly with voltage at a constant temperature. However, the current through electronic devices, such as a diode or a transistor undergoes nonlinear variation with voltage.
- *Impedance Transformation*: The same electronic device may exhibit different resistances across the input and the output terminals.

All the above characteristics were first realized with triode, a vacuum tube device invented by Lee de Forest in 1906. Therefore the invention of triode may be regarded as the foundation of electronics and we may feel that electronics has been a reliable companion of mankind for more than a century. The continuous research and development throughout this long period has enriched human civilization with innumerable equipment and gadgets like television, mobile phone, satellite communication, Internet, and a metamorphosis of computer from mechanical to electrically operated instrument. The researches on electronics and allied subjects have contributed to other branches of science and technology, and have given rise to new interdisciplinary fields. Throughout the 20th century, electronics has contributed to the civilization so much and influenced the society up to such a great extent that one may compare the advent of electronics with milestones like the inventions of wheel, printed letter, and steam engine.

1.2 Evolution of Electronics

Electronics originated as a part of modern physics after the discovery of electron by British physicist, Joseph John Thomson (1856–1940) in 1897. The studies on the dynamics of electrons brought about a turning point in the researches on current electricity that led to the development of electronics. The era of electronics, as is commonly reviewed, commenced with vacuum tube devices, such as triode and pentode. Later transistors and other semiconductor devices replaced those. However, it is less known that actually semiconductor devices were invented prior to vacuum tube devices. German engineer Karl Ferdinand Braun (1850–1918) noted in 1874 the dependence of the total resistance of a point metallic contact on metallic sulfide. Jagadish Chandra Bose of India studied systematically, during 1899–1904, the effect of oxidation of different metals on the radiation detecting property and patented (application in 1901, patented in 1904) lead sulfide point-contact rectifier, which was America's first publication in the area of solid state physics. It is also worth mentioning that he invented other instruments for wireless telecommunication, such as horn antenna, experimentally analyzed the properties of electromagnetic waves and was able to produce the first microwave radiation in laboratory.

Though point-contact rectifiers found applications in electromagnetic wave detectors, the primitive metal-semiconductor rectifying devices could not flourish only because there was no well-established theory to explain their properties. The working principle behind the rectifying action and the theory of current transport through the metal-semiconductor junction were not known in those days. Several decades later, British mathematician Alan Wilson (1906–1995) formulated the transport theory of semiconductor in 1931 that was applied to metal-semiconductor contacts. German physicist Walter Schottky (1886–1976) and British physicist Nevill Mott (1905–1996) independently suggested the development of potential barrier due to stable space charge in semiconductor. A brief idea of metal-semiconductor contacts is given in Chapter 3.

1.2.1 Revisiting the History

Electronics got maturity as a combination of two different trends of research: development of wireless communication and invention of vacuum tubes, and subsequent replacement

Note: J. C. Bose's Pioneering Contributions

Bose at Presidency College (now University) carried out ground breaking experiments on generating, transmitting, and receiving electromagnetic wave. He was the inventor of horn antenna and the first to generate microwave radiation in laboratory. As the detector, he devised a system of mercury contact with galena, the latter being identified today as Group II–VI semiconductor. Bose did his research almost a decade ago of the invention of triode when there was no trace of electronics and the concept of semiconductor was unknown. IEEE (Institute of Electrical and Electronics Engineers), the world's largest technical professional organization felicitated him posthumously with a plaque (preserved at the Physics Department, Presidency University) with the following inscription.

IEEE MILESTONE IN ELECTRICAL ENGINEERING AND COMPUTING

First Millimeter-wave Communication Experiments by J. C. Bose, 1894–1896

Sir Jagadish Chandra Bose, in 1895, first demonstrated at Presidency College, Calcutta, India, transmission and reception of electromagnetic waves at 60 GHz, over a distance of 23 meters, through two intervening walls, by remotely ringing a bell and detonating gunpowder. For his communication system, Bose developed entire millimeter wave components such as a spark transmitter, coherer, dielectric lens, polarizer, horn antenna and cylindrical diffraction grating.

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by semiconductor devices. Telecommunication was the first successful application of electronics where the new features, namely rectification and power amplification achieved with electronic devices were implemented.

The concept of wireless communication germinated when Scottish mathematician James Clerk Maxwell (1831–1879) put forward (1865) the theoretical explanations of the propagation of electromagnetic waves in space and German physicist Heinrich Hertz (1857–1894) could generate (1887) such waves in the laboratory. Jagadish Chandra Bose executed pioneering research during 1895–1904 on experimental verification of the nature of electromagnetic waves and invented equipment such as horn antenna for transmission of the wave. Italian inventor Guglielmo Marconi (1874–1937) succeeded in communicating electromagnetic wave over long distance across the Atlantic Ocean (1901) and could commercialize the wireless telecommunication system.

Note: A Missing Link in Wireless Telecommunication

The trail of development of telecommunication from the days of Maxwell to modern radio, television and mobile phone is not continuous. In 1912, a famous ship named Titanic sank in the Atlantic that Marconi's wireless signal could span in 1901. Titanic possessed on board wireless transmitter but that failed to contact the nearby ships. It was not a mere accident but this mishap revealed that the then existing knowledge on wireless transmission was insufficient to build up a universal 'grammar' of telecommunication that we have achieved today. Now one can easily access foreign radio broadcasting or can send email internationally. In those days, there was no device for continuous amplification of the weak electromagnetic wave propagating in space. The importance of triode (1906) was not realized at large. The wireless technology could have remained captivated in its primitive stage, if electronic devices were not there into the picture with the features of rectification, amplification, nonlinearity and oscillation.

Based on the electric bulb (1883) constructed by American inventor Thomas Edison (1847–1931), British engineer John Fleming (1849–1945) devised (1904) a vacuum tube equipment containing two electrodes and got a unidirectional current flow with it. The device was termed as 'diode' because of its two electrodes and was named 'valve' because its action was similar to the valve controlling liquid flow. The process of allowing current in a single direction through this device was called rectification. Very soon, American inventor Lee de Forest (1873–1961) incorporated (1906) a remarkable change in the vacuum tube equipment by introducing a third electrode. The tri-electrode vacuum tube device, popularly known as 'triode' could amplify electrical power. Thus a new dimension was added to the use of electricity.

1.2.2 Trends of Development

Jacob Millman (1911–1991), a renowned writer of reference books on electronics narrated (Jacob Millman and Arvin Grabel, *Microelectronics*, *2nd Ed*., Tata McGraw-Hill, India, 2009) the perpetuation of electronics in the group of four 'C's.

- C for Components
- C for Communications
- C for Computation, and
- C for Control

It is stated earlier that wireless telecommunication was the first significant application of electronics. Lee de Forest, the inventor of triode himself founded the first radio station (1916) in the USA and very rapidly radio broadcasting was commercialized.

After the invention of transistor (1948) by American physicists William Shockley (1910–1989), John Bardeen (1908–1991) and Walter Brattain (1902–1987), semiconductor devices replaced rapidly valve-made circuits. The nonlinear current–voltage relationship and other properties similar to those of vacuum devices were obtained with semiconductor junctions also (chapters 3, 5 and 9). Moreover, the conductivity of the material could be changed easily by adding other materials as impurity, the process being known as *doping* (Chapter 2). Thus semiconductor-made components were being developed for various purposes.

It is peculiar but a fact that the Second World War had a strong influence on the development of electronics. A lot of electronic components and controlling devices, such as radar, metal-oxide-semiconductor field-effect transistor (MOSFET) (Chapter 9), operational amplifier (Chapter 11), modern computer and other digital systems were developed during that period for the sake of war equipment. Efforts were being made all the way to fabricate miniaturized circuits suitable for missiles and artificial satellites. American engineer Jack Kilby (1923–2005) first achieved the successful fabrication of integrated circuit (IC) (Chapter 12) in 1958. The word 'microelectronics' became popular after the invention of IC. Today's unlimited series of control systems ranging from domestic remote controls to guided missiles cannot be imagined without ICs.

The concept of computation with instruments is centuries old. All the computing equipment, from the ancient *abacus* to the first computer named *difference engine* constructed by Charles Babbage were mechanical instruments. The perception of computer changed radically during the electronic era. Instead of mechanical structures, the computer appeared as an assemblage of electronic circuits, first of vacuum tube devices and then replaced with transistors and ICs. The development of electronics changed not only the computer but the whole concept of instrumentation, recording and measurement in scientific and technological applications and consumer products. The expansion of mercury in thermometer, photographic films with chemical emulsion, acoustic musical instruments and many other appliances have got an electronic alternative.

1.3 Widespread Applications

Electronics has developed as a combination of science and technology. The construction of electronic devices and circuits is based on the concept of electrical engineering while the background theories have originated from fundamental physical and chemical sciences, and mathematics. The theory and application of electronic devices have enriched other theoretical and experimental sciences and technologies and have given birth of many new ideas. Some are introduced here.

- *Negative Resistance*: The presence of resistance in a current carrying circuit causes some voltage drop across it. Therefore, one might expect that any 'negative resistance', if possible, would establish an amplification of voltage. Electronic devices have realized the concept of negative resistance. Some special electronic devices, such as Gunn diode, tunnel diode and IMPATT diode (all beyond the present scope of the book) can actually establish a negative resistance in a circuit. A few words on negative resistance will be stated in connection with the analysis of oscillators (Chapter 10).
- *Quantum Potential Well*: This is a theoretical model of quantum mechanics, which can be established experimentally with the technology of electronic devices.
- *Semiconductor Junctions*: In addition to the prevalent uses like rectification and voltage regulation and light emission (Chapter 3), the junction can be used as radiation detector in nuclear physics research. The presence of defects in the crystal structure can distort the simple energy band structure of a semiconductor (Chapter 2) and give rise to additional energy states, which can be investigated by studying the electrical properties of semiconductor and metal–semiconductor junctions.
- *Mathematical Modeling*: The studies on carrier transport in electronic devices have given rise to useful mathematical techniques, such as pseudopotential method, dangling bond treatment and filter transfer function, and many others, which are useful to other branches of physical science also.

Collaboration of electronics with other subjects have launched important interdisciplinary subjects. A few are elicited here.

- *Optoelectronics*: It is concerned with devices, such as light-emitting diode, laser, photodiode and solar cell that are meant for optical to electrical conversion and vice versa. Propagation of optical signal through glass or plastic fibers, known as fiber optical communication is a promising field of applications.
- *Information Technology*: It is a fusion of electronics, computer science, telecommunication, and statistics, and is concerned with data management, data mining, data-compression, cryptography, and many efficient transfer of information.
- *Medical Electronics*: Instruments, such as ECG, brain scanner, digital glucometer, digital sphygmomanometer, and laser eye surgery are electronic and optoelectronic instruments devoted to medical treatment and biodiagnostics.
- *Remote Sensing and Satellite Communication*: The techniques for observing the earth from space and spanning the continents through telephone and computer network acquired maturity with electronics.
- *Nanotechnology*: Collaborative researches on materials science and device fabrication technique have made it possible to construct electronic devices at molecular scale. Instead of 'microelectronics', the term 'nanoelectronics' is becoming popular. The nanoelectronic devices are produced with new fabrication techniques and these have size-dependent properties. The same material and its nanostructure counterpart, such as silicon and porous silicon, carbon and carbon nanotube are different. The nanostructure may exhibit novel electrical, optical or mechanical properties that are not available at macroscale.

As reviewed above, electronics has enriched science laboratories, technologies, and daily life. It has influenced human lifestyle and has become a significant component of today's economy, society, and human thought. It is not unreasonable to conclude as:

- if the invention of wheel and the discovery of fire have sublimed ape to man,
- if printed letter has given rise to renaissance,
- if steam engine has initiated industrial revolution,
- electronics has certainly created globalization of human civilization.

Perhaps one may add another 'C' to Millman's list to state 'C for Culture'.

1.4 Electrons, Electricity and Electronics

The history of science is often stranger than science fiction. Without knowing the fact that electric current through metallic wire is nothing but the flow of electrons, mankind had invented battery, dynamo and motor. Also the prime laws of current electricity including Ohm's law and Kirchhoff's laws were propounded prior to the discovery of electron. Nevertheless, the electronic artefacts were constructed consciously using the flow of electron, first with vacuum tube devices, such as triode, and then with semiconductor-made devices, such as the early transistors. The operation of electronic systems is somehow associated with electricity or movement of electrons, but it incorporates the flow of charge carriers through vacuum or semiconductor structures and emission of electrons from solids (Section 1.4.3), which are quite different phenomena in comparison with the simple flow of electrons in metals defined by Ohm's law.

1.4.1 Electric Current

Electric charge is the basic entity that assigns electrical property to an object. When two charged conductors are connected, charge flows from one to the other, and both objects acquire a common potential. This is an instantaneous and uncontrolled process. Rubbing a silk with a glass rod, discharging a capacitor, and thundering are such examples. When a constant potential difference is maintained between the conductors, a steady flow of charge termed as *electric current* takes place between them. The electric current is the rate of flow of charge through any area of a conducting material under the influence of a potential difference and it depends on

- the conducting property of the material medium quantified in terms of its *resistivity* or *conductivity*,
- the geometry of the object realized in terms of *resistance*,
- the motional property of the electric charges expressed in terms of *drift velocity* and *mobility*, and
- the potential difference and the surrounding parameters, such as temperature.

Think a Bit: Current, Current Density and Vector

Electric current has a direction but it is not vector because it does not obey the laws of vector addition. The sum or difference of 2 mA and 5 mA produces 7 mA or 3 mA only with the proper sign and nothing else. Current density is but a vector quantity because it describes how the charges flow at some point across a certain area. The vector direction informs the direction of charge flow at a point along a particular orientation of cross-sectional area. The current through a single conductor is the same at its all points but the current density increases and decreases according to the cross-sectional area of charge flow.

In the case of metallic conductors, the charge carriers are electrons only. Since the electrons are negatively charged, the direction of current is considered opposite to the direction of electron flow. In gases and electrolytes, both positive and negative ions contribute to the current but the net current occurs in a single direction; along the movement of positive charges. In vacuum, the electron flows in the form of a beam or stream that conducts current. Vacuum tube electronic devices utilize this process. Yet there is another material, named semiconductor, where the absence of electrons at a specific energy state is considered as

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positive charge and is termed as hole. Both electrons and holes contribute to the current in semiconductor devices, such as diodes and transistors. The salient features of electronics, namely electrical power amplification, nonlinear current–voltage relationship and impedance transformation within the device were first realized with vacuum tube devices and very soon the devices made of semiconductor devices replaced those made of vacuum tubes.

1.4.2 Drift Velocity, Mobility and Conductivity

In absence of any voltage and consequent electric field, the free charge carriers of a conductor undergo random motion in all directions due to thermal agitation, so that the resultant velocity is zero. When a voltage is established across the conductor, the electric field accelerates the charge carriers along it. Simultaneously the random motion and collision with atoms oppose the acceleration. As a combined effect, the carriers drift along the field with an average velocity called the *drift velocity*. In the case of metals, the charge carriers are electrons, which drift toward the higher potential, opposite to the direction of the electric field.

If an electron of mass m and charge e having initial thermal velocity $\vec{u}$ be accelerated by an electric field $\vec{E}$, its final velocity $\vec{v}$ just before a collision can be expressed as

$$\vec{v} = \vec{u} + \vec{a}\tau \tag{1.1}$$

where τ is the *relaxation time*, the short time for which a free electron accelerates before it undergoes a collision and $\vec{a} = e\vec{E} / m$ is the acceleration. Summing over all the electrons, the initial velocities are cancelled out and the drift velocity can be expressed as

$$v_d = \frac{eE}{m}\tau \tag{1.2}$$

Only the magnitudes are considered and the vector notations are avoided. Equation (1.2) indicates that the drift velocity is proportional to the electric field.

Let a conductor of length l and uniform cross-sectional area A contains n number of free electrons per unit volume. Then the total charge present in the conductor is $nelA$ and the time (t) taken in traversing the length of the conductor is l/v_d so that the current (charge/time) caused by these electrons is

$$I = neAv_d \tag{1.3}$$

Equation (1.3) expresses the current through a conductor in terms of electron drift velocity and the area of cross-section of the conductor.

The drift velocity acquired under unit electric field applied across the conductor is termed as *mobility* (μ) given by

$$\mu = \frac{v_d}{E} \tag{1.4}$$

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where E is the magnitude of the electric field. The SI unit of mobility is $\mathrm{m^2V^{-1}s^{-1}}$. Using Equations (1.3) and (1.4),

$$I = ne\mu AE \tag{1.5}$$

Equation (1.5) expresses the current in terms of carrier mobility. Using Equations (1.2), (1.4) and (1.5), we have

$$I = \frac{e^2 nAE\tau}{m} \tag{1.6}$$

If V be the voltage applied across the conductor of length l, the electric field (E) is V/l. Then equating Ohm's law with Equation (1.6) the resistance (R) can be obtained as

$$R = \frac{V}{I} = \frac{m}{ne^2\tau}\frac{l}{A} \tag{1.7}$$

From Equation (1.7), the resistivity (ρ) of the material (when $l = 1$, $A = 1$, $R = \rho$) can be identified as

$$\rho = \frac{m}{ne^2\tau} \tag{1.8}$$

From Equations (1.6) and (1.8), the magnitude of the current density can be derived as

$$J = \frac{I}{A} = ne\mu E = \frac{E}{\rho} \tag{1.9}$$

so that

$$\rho = \frac{1}{ne\mu} \tag{1.10}$$

Also from Equations (1.4) and (1.9),

$$J = nev_d \tag{1.11}$$

Think a Bit: Which Parameters Drift Velocity Depends On?

Equation (1.2) states that the drift velocity (v_d) of carriers in a conductor is proportional to the electric field (E) across it. However, using Equations (1.9)–(1.11) you will be able to derive the following expression for v_d.

$$v_d = \frac{V}{ne\rho l}$$

This implies that the drift velocity also depends on the geometry of the conductor. As the length (l) increases, the drift velocity decreases.

The SI unit of resistivity is Ωm. The inverse of resistivity is called conductivity (σ), which can be obtained from Equation (1.10) as

$$\sigma = ne\mu \tag{1.12}$$

The SI unit for conductivity is siemen (S).

Another useful relation can be derived from Equations (1.9) and (1.12) as

$$J = \sigma E \tag{1.13}$$

Equation (1.13) represents another form (vector form) of Ohm's law that has general validity. The familiar relationship $V = IR$ for bulk current is not valid for semiconductors. Equation (1.13) holds good at micro level. All the above concepts on drift velocity, mobility and conductivity are valid for semiconductors also. However, there exist the contributions of two types of carriers, electrons and holes, which have different values of mobility and other parameters. These topics are explained in detail in Chapter 2.

1.4.3 Electron Emission from Metal

Some electronic devices and related systems require the electrons to physically come out of the metal kept in vacuum. The outermost electrons in a metal are loosely associated with the ion core and can move freely within the metal boundary leading to its high conductivity. However, the electrons cannot escape the metal surface under ordinary conditions because of the net inward attraction of the positive ions. The electron must gain sufficient energy to overcome the attractive force. The highest energy level possessed by the electron at absolute zero is called the *Fermi energy*. The minimum amount of energy that must be given to the electron at the Fermi energy level so that it can escape the metal surface is called the *work function* of the metal. Such electron emission from metal surface can be caused by different energy sources, as stated below.

(i) *Thermionic Emission*: Thermal energy is supplied to the electrons by heating the metal in vacuum. The vacuum tube electronic devices like diode and triode utilize thermionic emission for generating electron flow in vacuum.

(ii) *Photoelectric Emission*: The metal is exposed to electromagnetic radiation of frequency (υ) greater than a certain critical value such that the photon energy (hυ) is greater than the work function. The emission is enhanced with the intensity of radiation. An optoelectronic device named photomultiplier tube emits electrons by this process.

(iii) *Field Emission*: This is also termed as cold cathode emission. At room temperature, electrostatic energy is supplied by applying a strong electric field caused by high positive voltage. Stronger electric field gives rise to greater emission. Electron microscope and carbon nanotube employ this technique.

(iv) *Secondary Emission*: Electrons or ions moving with high kinetic energy colliding with metal surface transfers the energy to the electrons inside the metal so that the electrons escape the metal surface. The scanning beam of electron microscope is an example of this process.