MATERIALS AND COMPONENTS IN ELECTRICAL ENGINEERING

Brett D Nener
The University of Western Australia, Australia.

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Contents

1. Introduction
2. Conductive Materials, Wires and Cables
3. Dielectric Materials and Devices
4. Semiconductor Materials and Devices
5. Magnetic Materials and Devices
6. Superconducting Materials and Devices
7. Fiber Optic devices and Systems
8. The Future
Glossary
Bibliography
Biographical Sketch

Summary

A broad-brush review of materials important to electrical engineering is given separated into the following categories: Conductive Materials, Wires and Cables; Dielectric Materials and Devices; Semiconductor Materials and Devices; Magnetic Materials and Devices; Superconducting Materials and Devices; Fiber Optic Devices and Systems. The fine details can be found in the articles of this topic under the above headings. The history is presented and the future trends are indicated.

1. Introduction

All of electrical engineering is founded on the interaction of electricity and magnetism within material systems. Materials and components permit the realization of concepts imagined by humankind. They also determine the limits of this realization.

From the time of the discovery of the electrostatic attraction resulting from rubbing amber and the description by Lucretius of the stone from the territory of the Magnesians that attracts iron, materials have been instrumental in the development of our exploitation of electricity and magnetism. There are a number of important milestones along the path of our understanding of materials. In this chapter we start the journey in the year 1600 when William Gilbert published “De Magnete.” This treatise marked the transition of electricity and magnetism from the realm of legend and magic into the experimental laboratory. The discovery by Stephen Gray in 1729 that charge could be transmitted from place to place through materials we now call conductors but could not be transmitted through materials that were amber-like, materials we now call insulators, was the germination of the application of electricity. The invention of the Leyden Jar, a form of capacitor, by Ewald von Kleist in 1745 led to incremental growth. However, it was not until a continuous source of electricity was demonstrated by Volta in 1799 that electricity could be controlled enough to explore its properties that the field grew strongly. Conductors were the key to the development of electricity and their importance continues to today.

In 1820 Oersted showed that an electric current could affect a magnet, thus showing that there was a connection between electricity and magnetism. This led Ampere to postulate that permanent magnets were due to currents on a molecular scale within the within the magnet. In 1821 Faraday, perhaps the greatest experimentalist showed that he could cause a wire to revolve around a magnet, the first electric motor. In 1831 he demonstrated induction of a current by movement of a magnet which later led to the electric generator. Faraday investigated many magnetic materials categorizing those that aligned across the magnetic field under the description diamagnetic and those that aligned with the field under the description paramagnetic. Those that behaved like iron he grouped under ferromagnets.

Ohm published his famous law showing that current and voltage were not independent in 1826-7. In 1827 Ampere published a mathematical theory of electricity, planting the roots of electricity and magnetism in fertile ground. In 1939, the first commercial telegraphs system was established on the Great Western Railway in England. This marked the transition of electricity from the laboratory into the public. The first commercial application of electric power was for street lighting in 1882 in New York and London by Edison's group of companies. This required a network of conductors to be distributed to carry the voltage for the incandescent globes of the day. Copper losses, the waste of energy from heating of the conductors, and the increase in the voltage drop with distance from the dynamo were major considerations of the day.

In 1911, Onnes demonstrated virtually zero resistance in mercury at the liquidification temperature of Helium. This was a new state of matter called superconduction. Today many exotic and complex combinations of materials are being investigated to find materials that show superconductivity at temperatures close to room temperature. This is an area with enormous potential for energy saving.

In 1845 Faraday showed that he could influence the polarization of light passing through a thick glass plate using magnetism. James Clerk Maxwell, the unifier of the laws of electricity and magnetism, described these experiments as the beginning of the marriage of light and electricity. In 1875 John Kerr discovered materials that demonstrated the effect of electricity on light but it was not until nearly a century later that these materials could be exploited in fiber-optic and electro-optic systems.

In 1947, the transistor was invented. This component had a revolutionizing impact on the later half of the 20^{th} century. It enabled the production of reliable computers on the desk-top that have relieved humankind from many onerous tasks and permitted the simulation of expensive or dangerous experiments. Along with the semiconductor laser it has been instrumental in the development of high speed, high bandwidth telecommunications that our information society depends on. The story of semiconductors goes back to the early work on radio detectors and in particular detectors for radar developed during the second world-war. The start was probably the observation by F Braun in 1874 of the rectification property of a metal contact on galena (lead sulfide). The story of the semiconductor is one of impurities. While silicon and germanium were in use as radio detectors it was clear that to operate at short wavelengths required purer material. A phenomenal effort, spurred on by economic potential, to refine these materials not only led to greater understanding of their operation but it was in fact the impurities themselves that determined the electronic properties of the material. Today there is more known about silicon than any other element.

2. Conductive Materials, Wires and Cables

The purpose of wires and cables is to transfer energy or/and information from one place to another with minimum leakage. They can be bare conductors or have an insulating cover. The choice of conductors or cables depends on many factors: electrical properties, mechanical properties, the working environment, cost of maintenance, handling costs, and the cost of the cable supports as well as the initial cable cost itself.

The electrical resistance per length and the maximum number of amps the conductor can carry are the most important electrical properties. The resistance per length depends on the conductivity of the metal and its cross-sectional area. The conductivity is determined by the choice of metal. Silver and gold are expensive conductors but are used in applications where high conductivity or corrosion-resistance outweighs the extra cost. Copper and aluminum are common metals used in conductors. Impurities in the metal reduce significantly the conductivity. Increase in temperature also reduces the conductivity. There is continuing development of new materials such as composites that may lead to significant cost savings and greater sustainability yet reasonable conductivity. The current carrying capacity is determined by the wire diameter and the number of strands. Industry has standardized conductor sizes. The selection of one of these common standards can lead to significant cost savings in reduced inventories and ease of procurement even if the current carrying capacity is more than required.

Tensile strength is a key mechanical property of conductors. Commonly, wires are made from copper or aluminum by drawing the metal through a die. The drawing process hardens the wire, reducing its flexibility but increasing its tensile strength. The as-drawn wires are used where mechanical strength is also important. A steel core can also be added for extra strength. At times, shock and vibration need to be taken into consideration. A flexible conductor consists of a number of strands of wire of circular cross section; 3, 7, 19, 37, 61, 91, 127, or 169 strands are usually used because these give a cylindrical form. Annealing the wires makes them soft and ductile and more suitable for windings or panel wiring.

The atmospheric surrounding of the cable or the likelihood of liquid ingression are the environmental factors that determine their choice. Wires are sometimes tinned to reduce interaction between the metal and the insulator. Explosive or corrosive atmosphere needs special consideration. Ingression by gases such as chlorine or liquids like water or fuel can seriously affect performance and safety.

Conductor selection can be complex. For example, as the diameter of the conductor increases, the weight increases, increasing the cost of the conductor as well as the support and installation costs. However, the resistance decreases with diameter and hence the line heating is reduced and the cable is able to carry greater power with reduced voltage losses. The wide spread of aluminum transmission lines over copper is because the specific gravity of aluminum is about a third that for copper with a conductivity still of about 60% that of copper.

On the small scale of integrated and printed circuits there is continuing research into new materials to increase conductance, reduce interaction with other materials and improve reliability. On the large scale, such as in power networks, there is a significant inertia due to the expensive infrastructure to overcome before new materials can be considered. For example, superconductors have the potential to reduce energy loss but the expense in comparison to the current technologies means that it will be a long time before they will be used widespread.

3. Dielectric Materials and Devices

Dielectrics serve two purposes: insulation and increase in charge storage.

Insulation is used to isolate regions. The measure of isolation is the leakage current across the dielectric for a given electric field strength. Considerations for cable insulator selection are the loss factor, and break down voltage resistance to conduction at high fields. Insulators are usually solid or gas and have a high resistance to conduction. Gas insulators have the advantage of being self -healing after break down conditions are removed whereas solids require a safety margin to ensure reliable operation. The thicker the insulation the greater the isolation but obviously they are bulkier. A measure of insulator quality independent of thickness is the dielectric strength, a measure of the material's ability to withstand voltage gradients.

Charge or energy storage can be enhanced in capacitors by the use of dielectrics. The relative permittivity of a dielectric is the factor by which the dielectric increases the charge stored in a capacitor compared to free-space. The increase in charge storage capacity is due to polarization, the separation of positive and negative charges, within the dielectric. The cause of this separation is the electric field and the ease of polarization is related to the strength of the bonds between the charges and the density of these dipoles. Like materials will have a comparable relative permittivity. For example poly-carbons have a relative permittivity of about 2, relative permittivity of semi-conductors is about 10 and water is about 80.

At low frequencies the polarization in a dielectric is in phase with the driving voltage but the current through the dielectric is ninety degrees out of phase; there is no power loss and energy is stored. The charge separation in the dielectric takes time to respond. This relaxation time is related to the bond strength of the material. For example, while the permittivity of water changes little, in the transition from solid to liquid, the response time changes significantly. As the frequency of the driving voltage increases the phase difference between the generation of the polarization and the applied voltage becomes significant. The polarization out of phase with the voltage represents an energy loss. This effect can be expressed as a complex permittivity as a function of frequency.

In small scale systems, particularly in high-frequency uses, ceramic capacitors play a major role. Ceramic capacitors now come in many different package forms mostly driven by the needs of surface-mount technology and the drive for miniaturization.

Traditional insulators in the power industry are porcelain and glass. The use of polymeric insulators has significantly increased in the last few decades. These new materials offer several advantages: lightness, compactness, robustness, high strength to weight ratio and moldability. However, because polymeric insulators are a relatively new technology there are questions on the long term performance. Testing methods and standards need to be developed to ensure the quality. Certainly porcelain and glass have a long track record. It seems clear that polymeric insulators will dominate the industry in the future.

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Biographical Sketch

Brett Nener received his BE(Hons) in 1977 from The University of Western Australia. He was awarded a Japanese Ministry of Education (Monbusho) scholarship to complete his MESc at the University of Tokyo. He was awarded his PhD in 1987 and is a Senior Member of the Institute of Electrical and Electronic Engineers (USA). He worked as a research engineer in industry before returning to academia. He currently teaches semiconductor device physics, and low noise and high frequency circuit design at The University of Western Australia. He has published numerous scholarly articles on modeling and measurements of atmospheric optical propagation, gallium-nitride electronic devices, and IR and UV detection and has held invitational positions as a visiting professor at universities and research institutions in the USA.