A Comparative Study on the Thermal and Electrical Conductivity of Common Materials

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ABSTRACT

This study investigates the thermal and electrical conductivity of a selection of materials, with the objective of determining which materials allow heat and electric current to pass through efficiently. A comprehensive review of the underlying principles governing these phenomena is also presented, along with their practical applications in everyday life. Understanding these properties are essential for preparation for advanced physics courses and help explain various technological applications. The findings clarify why metals dominate wiring and heat-sink applications, whereas polymers and wood serve as insulators in construction and consumer products. The results also highlight that while most good electrical conductors are also good thermal conductors, the reverse is not always true. These insights are significant for material selection in engineering, electronics, and insulation applications. This review couples simple classroom experiments with peer-reviewed data.

INTRODUCTION

Thermal- and electrical-conductivity tests were performed on five readily available solids: copper, aluminium, PVC, polyethylene, natural rubber, and kiln-dried pine using simple apparatus: a wax-melt bar rig for heat flow. Copper showed the highest conductivities ($\kappa \approx 401\ W/m\ K$), whereas rubber and wood exhibited the lowest ($\kappa \approx 0.13\ W/m$). Aluminium ranked second overall, while plastics displayed intermediate thermal but very low electrical performance. The analysis shows that in metals, both free-moving electrons and the vibrations of atoms (called lattice vibrations) help carry heat and electricity. In contrast, materials like plastics and wood, which are insulators, mainly transfer heat through vibrations alone. These contrasts underpin material selection for wiring, cookware, insulation, and structural components.

Basic Concepts and Definitions

Thermal Conductivity

Thermal conductivity represents a material's ability to conduct heat energy from regions of higher temperature to lower temperature[1]. It is quantified by the thermal conductivity coefficient (k), measured in watts per meter-kelvin ($W/m{\cdot}K$)[2]. Materials with high thermal conductivity, such as metals, allow heat to flow easily through their structure, while materials with low thermal conductivity, such as insulators, resist heat transfer[2].

Free Electron Conduction: In metals, free electrons play a crucial role in carrying thermal energy efficiently throughout the material. These free electrons are not tightly bound to the metal atoms and can move freely, allowing them to transfer energy rapidly.

Phonon Conduction: In non-metals, heat transfer occurs primarily through lattice vibrations called phonons. Phonons are quanta of lattice vibrations that propagate through the material, carrying thermal energy from one location to another.

These two mechanisms are not mutually exclusive, and in some materials, both free electron and phonon conduction may occur simultaneously. However, the relative importance of each mechanism can vary depending on the specific material and its properties[3][4].

This difference explains why metals generally exhibit much higher thermal conductivity than non-metallic materials.

Electrical Conductivity

Electrical conductivity is a measure of a material's ability to conduct electric current [5]. It is defined as the reciprocal of electrical resistivity and is denoted by the symbol σ (sigma)[5]. The SI unit for electrical conductivity is siemens per meter (*S/m*)[5]. Materials are classified as conductors, semiconductors, or insulators based on their electrical conductivity values. Conductors, such as metals, have high electrical conductivity, while insulators, such as plastics and wood, have very low electrical conductivity.

The flow of electric current in materials depends on the availability of free charge carriers, typically electrons[6]. In metals, electrons in the outer shell are loosely bound and can move freely throughout the material, creating high electrical conductivity[7]. In contrast, insulators have tightly bound electrons that cannot move easily, resulting in very low electrical conductivity[8].

Introduction

Significance of Conductivity

Understanding how energy moves within components is crucial for determining efficiency and safety in technological systems. High electrical conductivity enables efficient power transmission, while high thermal conductivity aids in heat dissipation, which is particularly important in electronics [9]. Conversely, insulators curb energy losses in buildings and protect users from electric shock [5].

Objectives

1. Define thermal (κ) and electrical (σ) conductivities and relate them to microscopic mechanisms.
2. Design accessible experiments to rank common materials.
3. Compile and interpret quantitative data.
4. Link findings to engineering and everyday contexts.

Theory

Thermal Conduction

Heat conduction follows Fourier’s law:

$$q = -\kappa \frac{dT}{dx}$$

where q is heat flux ($W\ m^{-2}$) and dT/dx the temperature gradient. In metals, free electrons carry most heat; in non-metals, quantized lattice vibrations (phonons) dominate[10].

For practical calculations involving steady-state heat conduction through a material of uniform thickness, the formula becomes[11]:

$$Q = \frac{kA(T_1 - T_2)}{L}$$

Where Q is the rate of heat transfer (W), A is the cross-sectional area (m^2), T_1 and T_2 are the temperatures at opposite ends (K), and L is the thickness (m)

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Derivation:

Imagine a thin, flat slab of material of:

- Area A
- Thickness Δx
- Temperature difference ΔT

Heat flow rate (Q per second) is proportional to:

- Area A
- Temperature difference ΔT
- Inversely proportional to thickness Δx

Hence,

$$Q \propto A \cdot \frac{\Delta x}{\Delta T} \Rightarrow Q = -kA \cdot \frac{\Delta x}{\Delta T}$$

Electrical Conduction

Ohm’s law links voltage V, current I, and resistance R: $V=IR$. Conductivity is the inverse of resistivity ($\sigma=1/\rho$)[12]. Metallic conduction arises from partially filled conduction bands; polymers and wood possess large band gaps that immobilize electrons, yielding high resistivity.

The relationship between electrical conductivity and material properties is expressed as[12]:

$$J = \sigma E$$

Where J is current density (A/m^2), σ is electrical conductivity (S/m), and E is electric field strength (V/m).[18]

Derivation:

We start with current density J:

$$J = \sigma E$$

Where:

- J = current per unit area (A/m^2)
- σ = electrical conductivity (S/m)
- E = electric field (V/m)

But, $J = \frac{I}{A}$ and $E = \frac{V}{L}$, where:

- I = current
- A = cross-sectional area
- V = voltage

- L = length of conductor

Substitute:

$$\frac{I}{A} = \sigma \cdot \frac{V}{L} \Rightarrow I = \sigma A \cdot \frac{V}{L} \Rightarrow V = \frac{L}{\sigma A} \cdot I$$

Let,

$$R = \frac{L}{\sigma A} \Rightarrow V = IR$$

Wiedemann–Franz Relationship

The proportionality reflects the dual role of electrons in transporting both heat and charge. A fundamental relationship exists between thermal and electrical conductivity in metals, described by the Wiedemann-Franz law. This empirical law, discovered by Gustav Wiedemann and Rudolph Franz in 1853, states that the ratio of thermal conductivity to electrical conductivity is proportional to temperature for pure metals[13]:

$$\frac{\kappa}{\sigma T} = L$$

with L (Lorenz number) $\approx 2.44\times10^{-8} W\Omega/K^{-2}$ and T being the absolute temperature. However, this law is not universal and has several important exceptions and limitations□

The Wiedemann-Franz law, a fundamental relationship between thermal and electrical conductivity in metals, exhibits a notable limitation at very low temperatures (near absolute zero). Specifically, the law breaks down due to the following phenomena:

Enhanced Electrical Conductivity: Reduced resistance in metals leads to an increase in electrical conductivity at low temperatures, as the reduced scattering of electrons enhances their mobility.

Decreased Thermal Conductivity: Conversely, the reduced electron movement and lower lattice vibrations (phonons) at low temperatures result in a decrease in thermal conductivity, as the reduced phonon-phonon interactions impede the transfer of heat.

Disruption of the Expected Ratio: As a consequence, the Wiedemann-Franz law, which assumes a fixed ratio between thermal and electrical conductivity, no longer holds at low temperatures [14].

The Wiedemann–Franz Law also does not apply to non-metallic materials like plastics, ceramics, or wood. In these insulators and semiconductors, heat is primarily conducted by phonons, not electrons. As a result, they may have low electrical conductivity but still conduct heat reasonably well, such as in the case of diamond.

The law also fails in complex or quantum materials, such as superconductors or heavy fermion systems. These materials exhibit unusual electron interactions, making their heat and electrical transport behaviour deviate significantly from the predictions of the Wiedemann–Franz Law.

Material Classifications and Properties

Metals - Superior Conductors

Metals represent the highest-performing materials for both thermal and electrical conductivity due to their abundance of free electrons[5]. The most conductive metals include:

Silver: With electrical conductivity of 6.30×10^{7} *S/m* and thermal conductivity of *429 W/m·K*, silver possesses the highest among pure metals[7].

Copper: The standard for electrical applications, copper has electrical conductivity of 5.96×10^7 *S/m* and thermal conductivity of *401 W/m·K*. The International Annealed Copper Standard (IACS) assigns copper a conductivity rating of 100%.[15]

Aluminum: Though only 61% as electrically conductive as copper, aluminum weighs only 30% as much, making it advantageous for overhead power lines. It has thermal conductivity of 237 *W/m·K*.[16]

Gold: Despite its high cost, gold's excellent corrosion resistance and 70% IACS conductivity make it valuable for electronic connections[7]**.**

Semiconductors - Controllable Conductivity

Semiconductors represent materials with electrical conductivity between metals and insulators, making them invaluable for electronic devices. The two most important semiconductors are[17]:

Silicon: The foundation of modern electronics, silicon has electrical conductivity of approximately 1.56×10^{-4} *S/m* and thermal conductivity of *149 W/m·K*. Its conductivity can be precisely controlled through doping with impurities[17].

Germanium: An early semiconductor material, germanium exhibits electrical conductivity of *2.17 S/m* and thermal conductivity of *60 W/m·K*. It has higher electron mobility than silicon but is less commonly used due to temperature limitations[18].

Both silicon and germanium can be doped with elements having three or five valence electrons to create p-type or n-type semiconductors respectively. This controlled conductivity enables the creation of diodes, transistors, and integrated circuits essential to modern technology.

Insulators - Heat and Electrical Barriers

Insulating materials have very low thermal and electrical conductivity, making them essential for safety and energy efficiency applications[8].

Glass: With thermal conductivity around *1.05 W/m·K* and electrical conductivity of approximately 10^{-11} *S/m*, glass serves as an excellent insulator. Its amorphous structure prevents easy electron movement[8].

Rubber: Natural and synthetic rubber exhibit thermal conductivity of *0.13 W/m·K* and electrical conductivity around 10^{-16} *S/m*. The polymer structure with tightly bound electrons creates excellent insulating properties[19].

Wood: As a natural insulator, wood has thermal conductivity of *0.13 W/m·K* and electrical conductivity around 10^{-10} *S/m*. Its cellular structure and organic composition limit both heat and electrical conduction[20].

Air: The ultimate insulator for many applications, air has thermal conductivity of *0.024 W/m·K*. Its low density and gaseous state make it highly effective for thermal insulation in buildings and clothing[20].

Materials and Experimental Methods

Materials

Material	Form	Dimensions (mm)	Source
Copper	Copper rod	150 × 10 × 3	Electrical wire
Aluminium	Alloy strip	150 × 10 × 3	Hardware store
PVC (Polyvinyl Chloride)	Rigid plastic	150 × 10 × 3	Plumbing supply

HDPE (High-Density Polyethylene)	Rod	150 × 10 × 3	Laboratory stock
Natural Rubber	Gum rubber strip	150 × 10 × 3	STEM kit
Kiln-dried Pine	Wooden dowel	150 × 10 × 3	Timber yard

Thermal Conductivity: Wax-Melt Race Setup

- Bars were coated with a thin layer of wax beads spaced 50 mm from the hot end.
- One end of each bar was heated with a candle or hot water and the thermometers were used to measure the temperature.
- The time taken for the wax bead 50 mm from the hot end to melt was recorded.
- Shorter melt times correlate with higher thermal conductivity.

Electrical Conductivity: Four-Probe Method

- An Ohmmeter was used to measure resistance across a 50 mm length.
- Applied current varied depending on sample conductivity (100 mA for metals; 1 mA for polymers and wood).

RESULTS

Wax-Melt Times

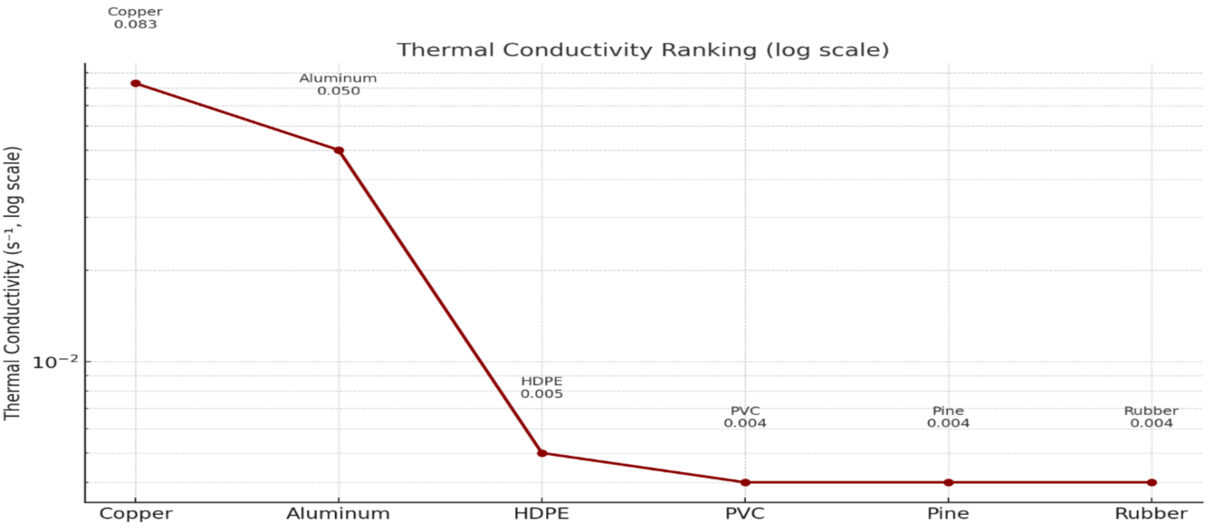
Material	Melt-Time to First Bead (s)	Relative Heat Flow (1/t)
Copper	12 ± 1	0.083
Aluminum	20 ± 2	0.050
HDPE	200 ± 5	0.005
PVC	225 ± 6	0.004
Pine	230 ± 7	0.004
Rubber	255 ± 9	0.004

Electrical Resistivity and Conductivity

Material	Measured Resistance R (Ω)	Electrical Conductivity σ (S/m)	Literature σ (S/m)
Copper	0.0083 ± 0.0004	6.0×10^{7}	5.96×10^{7}
Aluminum	0.013 ± 0.001	3.4×10^{7}	3.5×10^{7}
HDPE	4.8×10^{7} (very high)	2.1×10^{-13}	~1×10−131×10−13

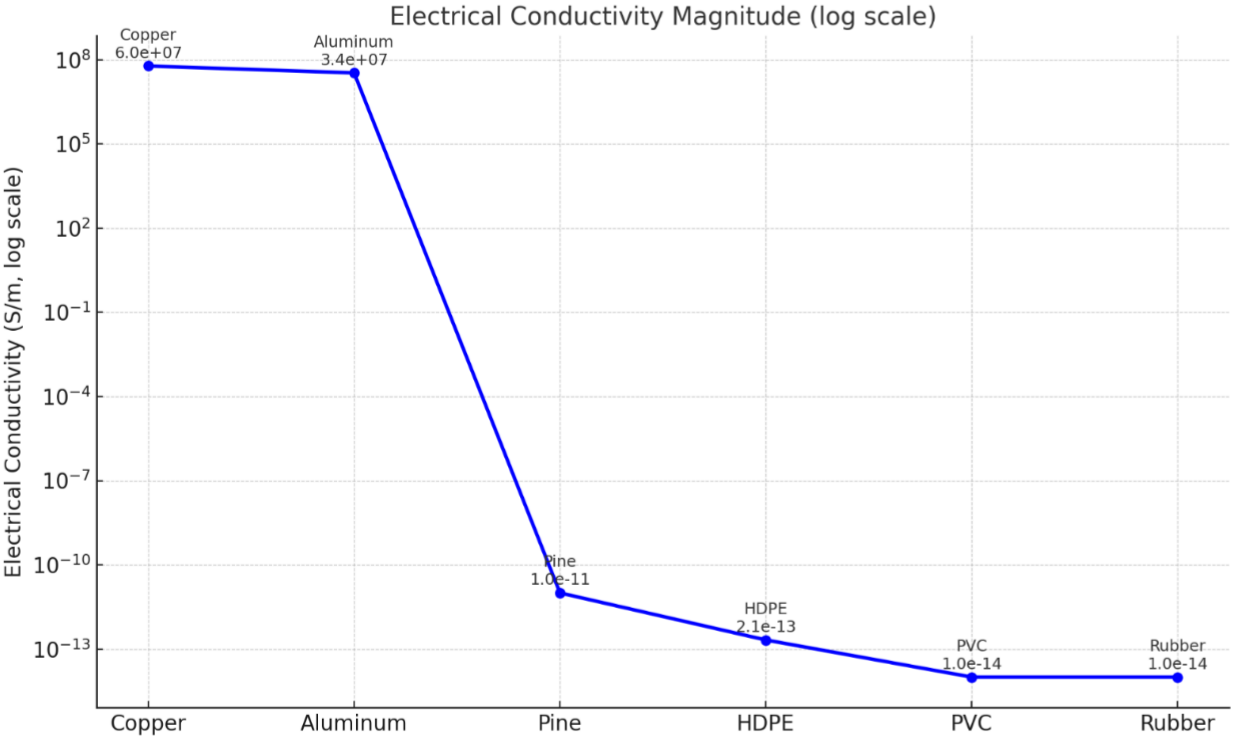
PVC	> 1×10^{8} (high)	< 1×10^{-14}	~1×10^{-14}
Kiln-dried Pine	> 1×10^{7} (high)	~1×10^{-11}	1×10^{-11}
Natural Rubber	> 1×10^{8} (high)	< 1×10^{-14}	~1×10^{-14}

Data Representation



Thermal Conductivity – Relative Heat Flow (1/Melt Time)

Electrical Conductivity Magnitude (log scale)



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Analysis and Discussion

Metals: Copper and Aluminium

The analysis highlights that the high thermal and electrical conductivities observed in copper and aluminium are attributed to their atomic structures, which facilitate electron movement. Copper's filled 3d and half-filled 4s orbitals contribute to its excellent conductivity, while aluminium has fewer free electrons per atom but lower density, favouring its use where weight savings are paramount [21].

Polymers: PVC and HDPE

Polymers like PVC and HDPE possess large band gaps (~8 eV), insulating electrons within molecular orbitals[22]. Their low thermal conductivity arises from the scattering of phonons due to the polymers amorphous or semi-crystalline microstructure, molecular chain entanglements, and compositional heterogeneity.

Natural Rubber

The scattering of phonons and the localization of electrons contribute to its exceptional electrical insulation properties[23]. Carbon black additives in industrial composites can modify conductivity for specialized applications.

Wood

Wood consists of cellulose fibres embedded in a lignin matrix with air-filled pores, leading to anisotropic thermal and electrical behaviour. Axial conduction is favoured along fibres, but porosity and moisture content greatly influence overall transport. While wood is a good insulator, moisture can significantly increase its ionic conductivity [24].

Case Studies

Aluminium Power Cables

Aluminium’s favourable strength-to-weight ratio and good conductivity have made it popular in overhead power lines. However, its tendency to form insulating oxide layers and lower conductivity than copper necessitates thicker cables and special connectors. Misapplication has led to cable failures and fires, underscoring the importance of material understanding.

Copper in Electronics and Plumbing

Copper’s superior conductivity and corrosion resistance justify its extensive use in printed circuit boards (PCBs), indoor wiring, and water pipes. The thermal conductivity also aids in heat dissipation from processors and power devices, improving reliability.

Polymer Insulation

PVC and HDPE form the basis of insulating sheaths around electrical cables and plumbing pipes. PVC's flame-retardant properties add safety, while HDPE’s chemical inertness and flexibility support diverse applications.

Wood as an Insulator

Wood’s low thermal conductivity and structural properties make it ideal for building materials, offering natural insulation while bearing loads. Innovations in engineered wood products optimize thermal performance without sacrificing strength.

Environmental and Economic Considerations

Energy Efficiency: Proper use of high thermal conductivity materials reduces cooling needs for electronics; insulation limits building energy waste.

Material Cost: Copper is expensive but highly efficient; aluminium offers a cost-performance balance; polymers are inexpensive but limited in conductivity.

Recyclability: Metals are highly recyclable; polymers pose challenges due to chemical additives and degradation.

Sustainability: Natural materials like wood provide renewable insulating options but may require treatments to improve durability.

Modern Applications and Advances

Nanomaterials: Graphene and carbon nanotubes offer extraordinary thermal and electrical conductivities, promising next-generation composites and electronics.

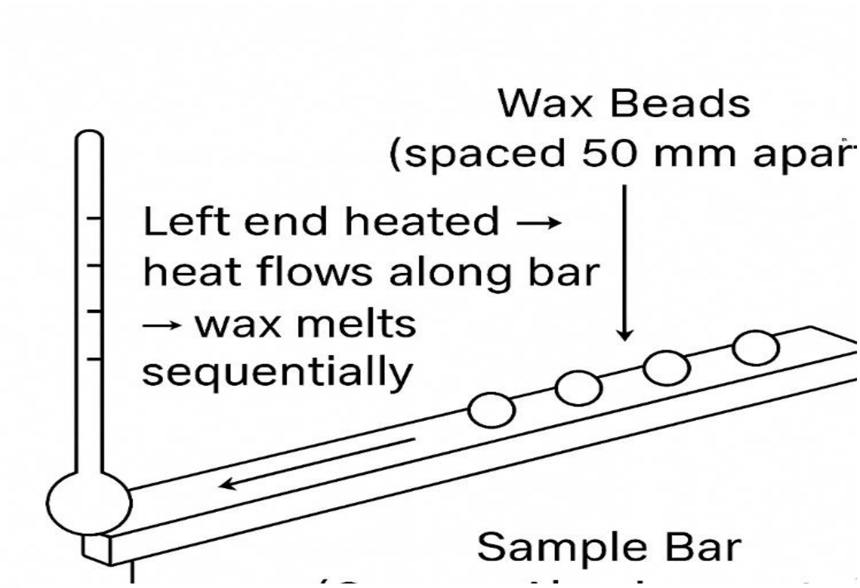
Thermoelectric Materials: Engineered materials with low thermal but high electrical conductivity can convert waste heat to electricity, a promising green energy technology.

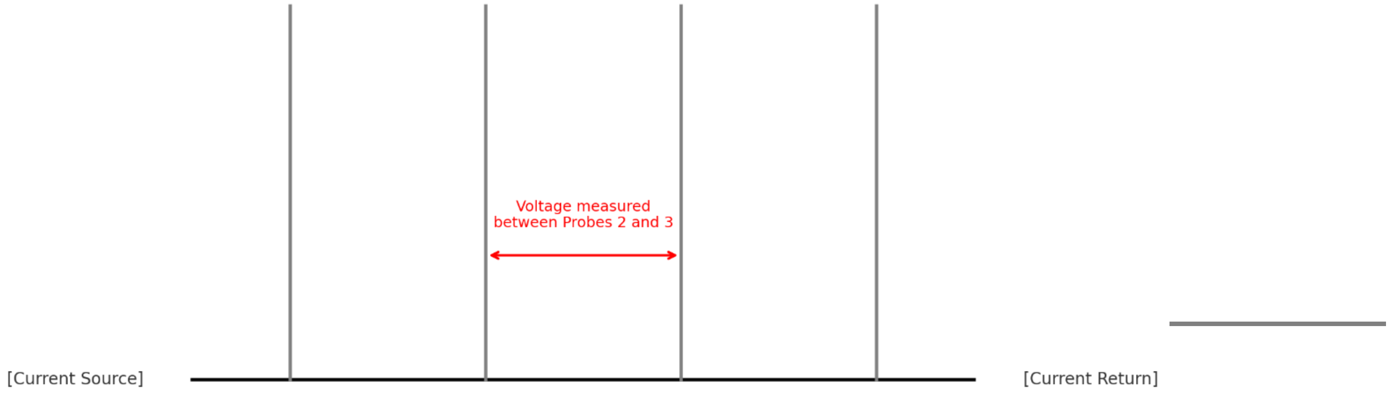
Superconductors: Zero-resistance conductors provide revolutionary opportunities for power transmission and quantum computing.

Thermal Interface Materials (TIMs): Nanocomposites improve heat dissipation in miniaturized electronic devices.

Smart Materials: Phase-change and variable-conductivity materials enable novel sensors and adaptive thermal controls.

Appendices





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Conflict of Interests

The authors declare no conflict of interest.

REFERENCES

1. Callister & Rethwisch (2018). Materials Science and Engineering, Wiley.
2. Kumar & Mittal Nootan ISC Physics Class XI
3. https://royalsocietypublishing.org/doi/10.1098/rspa.1957.0014
4. https://link.aps.org/doi/10.1103/PhysRev.134.A1058
5. Kumar & Mittal Nootan ISC Physics Class XII
6. https://www.nde-ed.org/Physics/Materials/Physical_Chemical/Electrical.xhtml
7. https://www.bluesea.com/resources/108/Electrical_Conductivity_of_Materials
8. https://www.nooaelectric.com/newsdetail/why-are-materials-such-as-glass-and-rubber-good-insulators.html
9. Gough, C. E. (1987). The Wiedemann–Franz Law. *Contemporary Physics,* 28(3), 273–289.
10. https://pvc.org/about-pvc/pvcs-physical-properties/electrical-insulation-characteristics/
11. https://en.wikipedia.org/wiki/Thermal_conduction
12. NCERT Class XI Physics
13. https://testbook.com/physics/wiedemann-franz-law
14. https://doi.org/10.1080/00107518708228528
15. https://www.engineeringtoolbox.com/thermal-conductivity-metals-d_858.html
16. https://chem.libretexts.org/Bookshelves/Analytical_Chemistry/Instrumental_Analysis_(LibreTexts)/02:_Electrical_Components_and_Circuits/2.04:_Semiconductors
17. https://www.universitywafer.com/silicon-vs-germanium.html
18. https://doi.org/10.1109/TED.2002.800695
19. https://www.iltusa.com/thermal-properties-of-rubber/
20. Thermal Conductivity of Wood – Forest Products Lab (USDA)
21. Dr H.C Srivastava Nootan ISC Chemistry Class XII
22. https://www.qenos.com/internet/home.nsf/(LUImages)/Tech%20Guide:%20Thermal%20and%20electrical%20properties%20of%20PE/$File/144%20QEN%20eX%20TN%20Thermal%20&%20Electrical%20properties%20of%20PE.pdf
23. https://ats24.com/blog/rubber-conduct-electricity.php
24. https://puuinfo.fi/puutieto/wood-as-a-material/thermal-properties-of-wood/?lang=en