Einstein's Equation

Electromagnetic waves travel through free space at a speed 3×10^8 ms^{-1} which is the highest value of speed of particles and mechanical waves. *Einstein* postulated in his well known relativity theory that speed of light has the same value for all observers, independent of the motion of the light source or observer. The relativity theory relates every physical quantity with velocity of light. The time dilation, length contraction, variation of mass with velocity, velocity addition, mass-energy equivalent etc. are main consequences of special theory of relativity.

The *Einstein's* equation is the relation between mass and energy i.e. mass can be converted into energy. The equivalence factor is velocity of light. This equation is used not only in wave-mechanical study but also in nuclear science. To derive this relation, let us consider a particle of mass m acted upon by a force F in the same direction as its velocity v produces a displacement dx. Thus the increase in kinetic energy of the particle is represented by work done (Fdx). Hence

$$dw = Fdx = \frac{d}{dt}(mv)\,dx$$

$$= \left(m\frac{dv}{dt} + v\frac{dm}{dt}\right)dx$$

$$dw = mvdv + v^2dm \qquad \left[\because v = \frac{dx}{dt}\right] A(1)$$

According to the variation of mass with velocity of the relativity theory,

$$m = \frac{m_0}{\sqrt{1 - \frac{v^2}{c^2}}}$$

or,

$$m^2 = \frac{m_0^2}{\left(1 - \frac{v^2}{c^2}\right)} \qquad A(2)$$

or,

$$m^2c^2 = m_0^2c^2 + m^2v^2$$

Differentiating it we get,

$$2mc^2dm = 0 + 2mdmv^2 + 2vdvm^2$$
$$c^2\,dm = mv\,dv + v^2\,dm$$

or,

Hence from equation $A(1)$ we have,

$$dw = c^2\,dm \text{ and integrating both sides}$$

$$w = c^2\int_{m_0}^{m} dm = c^2(m - m_0) \qquad A(3)$$

This is the relativistic formula for kinetic energy. At rest $m = m_0$ from $A(2)$, so m_0c^2 is the rest mass energy. Thus the total energy of the particle is

$$E = w + m_0c^2 = (mc^2 - m_0c^2) + m_0c^2$$
$$E = mc^2 \qquad A(4)$$

which is well known *Einstein's* mass energy relation which states that mass can be converted into energy or vice versa.

Collection of Particles

B **Appendix**

In general, there are $3N$ equations of motion of second order for a system containing N-particles, which needs three-dimensional space to specify a particle. Such space is known as configurational space. For general consideration, it is more convenient to write $6N$ partial differential equations of the first order in place of $3N$ equations of second order. For this purpose, there must be $6N$ degree of freedoms or $6N$ dimensional space called **Phase Space**. In this space, a single particle is specified by 3-position co-ordinates and 3-momentum co-ordinates.

The physical quantities of interest in a thermodynamic system are usually the time average over the trajectory of particles in the phase space. In general, calculation of time average is a very complex task. There are a very large number of orders of 10^{23} of particles in a system which interact with one another in a complicated manner. The detailed kinematics of all these particles is a hopelessly tedious task even for a very small or simple system like an ideal gas. But *Gibbs* and *Boltzmann* found statistical method by which we can easily calculate the averages and resolving the impasse.

There are large numbers of points in phase space, all of which correspond to the same macroscopic state. Each of these points would represents some systems and these systems will have the feature that their microscopic structures are different but their bulk behaviour is same. **A random collection of such system, each of which corresponds to the same macrostate but has different microstructure, is called an ensemble.**

The great importance of the ensemble concept arises from the remark of *Gibbs* that the average over a period of time for a given system is equivalent to the average over the ensemble at one instant of time. An ensemble may be visualized as a collection of systems which are virtual copies of the real system i.e. macroscopically identical to real system but in different microstate. A microstate is defined as the specification of the individual position of phase points for each system or molecules of the ensemble. Individual system or molecule in the phase space is called phase point. A phase may be divide into cells and the phase point for any system or molecules may reside in one of the cells.

MAXWELL-BOLTZMANN'S DISTRIBUTION

The *Maxwell-Boltzmann* distribution establishes the distribution of macrocopic particles in phase space subjected to the action of arbitrary potential field. The *Maxwell-Boltzmann* distribution is applicable in classical system having interacting particles in equilibrium. We use this distribution if the number of phase points in a cell is very much smaller than the number of compartments.

Let us consider particles that are distinguishable. The number of microstates corresponding to any given macrostate is called thermodynamic probability of the macrostate and the probability for N particles placing into cells and the ith cell having n_i particles is,

$$W = \frac{N!}{\prod n_i!} \qquad B(5)$$

For maximization of the probability, let us take log both sides

$$\log W = \log N! - \sum_i \log(n_i)!$$

Using *Stirling*'s approximation we get

$$\log W = (N \log N - N) - \sum_i (n_i \log n_i - n_i)$$

$$= N \log N - \sum_i N_i \log n_i . \text{ Since } \sum_i n_i = N$$

Differentiating the relation and using $d \log (W) = 0$ we get,

$$\sum \log n_i \, \delta n_i = 0 \qquad B(6)$$

Let the total energy of all n_i particles whose phase points lie in the ith cell is $E_i n_i$ and the internal energy of the system is then

$$U = \Sigma E_i n_i$$

The total energy of the system remains constant then,

$$\delta U = \Sigma E_i \delta n_i = 0 \qquad B(7)$$

We now use *Lagrange*'s method of undetermined multipliers to solve such equations $B(6)$ and $B(7)$. Thus for convenience let $\log \alpha$ be subtracted with $B(6)$ and along with $B(7)$ by multiplying β in such a way that

$$\sum_i (\log n_i - \log \alpha + \beta E_i) = 0$$

i.e. $$\log \left(\frac{n_i}{\alpha} \right) = - \beta E_i \text{ and } n_i = \alpha e^{-\beta E_i} \qquad B(8)$$

which is called *Boltzmann* distribution function of particles. A rigorous mathematical calculation shows that $\beta = \frac{1}{KT}$ and α identifies as the fugacity and is given by $\alpha = \frac{Nh^2}{V} (2\pi m k T)^{-\frac{3}{2}}$. V is the volume of the phase space and h is *Planck*'s constant.

Now the distribution function in general is expressed as

$$n_i = N e^{-\frac{E_i}{kT}} \qquad B(9)$$

However thus distribution cannot explain when there are large numbers of particles. It also cannot explain for microscopic particles such as electrons, protons, photon, phonon etc. These particles requires quantum distribution function such as *Fermi-Dirac* and *Bose-Einstein* distributions.

Some Typical Questions

1. Theory of Metal

(i) Describe the wave-particle duality with suitable examples.

(ii) Starting from ordinary wave equation in classical mechanics given by $y = A \sin\left(2\pi ft - \dfrac{2\pi}{\lambda}x\right)$

where all the notations have their own meaning, derive Schrödinger's equation in 1-dimensional

form $\dfrac{\partial^2 \psi}{\partial x^2} + \dfrac{8\pi^2 m}{h^2}(E - V)\psi = 0$.

(iii) What is the significance of work function in metals?

(iv) How to you understand wave function? What are its significances in quantum mechanical studies?

(v) Starting from general solution of Schrödinger's equation given by $\psi(x) = A \sin \beta x + B \cos \beta x$ where

$\beta = \left[\dfrac{8\pi^2 m}{h^2}(E - V)\right]^{1/2}$ prove that the energy of a particle confined in an infinite potential well is

quantized.

(vi) What are eigenvalues and eigenfunctions?

(vii) Define and describe Heisenberg's uncertainty principle. How do you interpret this principle? Explain your views with suitable examples.

(viii) Using Heisenberg's uncertainty principle, prove that the minimum kinetic energy of a particle

confined in an infinite potential well of width L is given by $E = \dfrac{\pi^2 \hbar^2}{2mL^2}$.

(ix) What are the significances of operators in quantum mechanical studies? Find the corresponding operator notations for energy momentum.

(x) Explain the behavior of particle confined to a potential box with finite barrier height. How is the particle wave function represented in the barrier region?

(xi) What is tunneling? Can you imagine the phenomenon identical to tunneling taking place in classical mechanics? How the wave function will be represented in either side of the narrow potential barrier that has been successfully tunneled through by the particle?

(xii) Show that for a linear solid, the energy is still quantized.

(xiii) Define number of states and density of states functions in quantum mechanics. Derive appropriate expressions for number of states and density of states.

(xiv) What is the application of Fermi function in quantum mechanics? Occupation index is highly temperature dependent. Justify.

(xv) Prove that Fermi energy in a metal is independent of temperature and depends only in its electron concentration.

(xvi) Using image charge method, derive the Richardson's expression for thermionic emission for Schottky effect.

(xvii) How the contact potential between two different metals with different Fermi levels can be employed to measure temperature of one of the metals?

(xviii) What is thermoelectric emf? Explain the Seebeck effect.

2. Free Electron Theory of Conduction in Metals

(i) Define lattice array, lattice parameter, packing density, Bravais lattices applicable to crystalline structures.

(ii) Find the packing densities of Si, Cu and Fe crystals.

(iii) Explain the procedures for identifying Miller indices for crystal direction and plane.

(iv) Explain the bonding in hydrogen molecule. What are bonding and anti-bonding molecular orbitals? Give reasons behind completely or partially filled bonding orbitals and vacant antibonding orbitals.

(v) Produce a neat sketch of Kronig-Penny model. Does this model correctly represent the electron within the crystalline structure?

(vi) What are the brilliouin zones?

(vii) Define and explain the effective mass of electron within a crystal. How do you understand negative and infinite effective mass of electron?

(viii) Starting from $PV = \dfrac{N m v^2}{3}$ for gas in a container, derive the expression for mean thermal velocity of

electron $v_{th} = (3kT/m)^{1/2}$.

(ix) Define drift mobility of electron, conductivity and resistivity applicable to metals.

(x) What are the factors that affect electrical conductivity in metals?

(xi) Derive $J = \sigma E$ for metals.

(xii) Electrical conductivity of metal is high although drift mobility of electrons in metal is low. Why? Explain.

(xiii) What are the factors that define the electron drift velocity in the metals? How temperature affects the electron drift mobility in metals? Is the same relationship applicable to semiconductors?

3. Conduction in Liquids and Gases

(i) What are the principal conduction mechanisms in liquids? Explain.

(ii) Explain the breakdown phenomenon in gases.

(iii) What are the principal conduction mechanisms in gases? Explain.

(iv) Explain the Townsend current growth mechanism.

(v) At normal temperature and pressure, gas is more likely to breakdown by an applied electric field than liquid dielectric.

(vi) How conduction starts in atmospheric air?

(vii) How frequently are the liquid and gaseous conductors used for current conduction purposes? Give some examples.

(viii) How the conduction in gaseous medium is different from that of solid metallic conductors? Explain.

4. Dielectric Materials

(i) How the macroscopic parameters are related to microscopic parameters in dielectric materials? Show.
(ii) Define dipole moment, polarization vector, polarizability.
(iii) How the electronic polarization takes place in an atom? Show that the magnitude of surface polarization charge density is equal to polarization vector.
(iv) How dielectric susceptibility is related to electronic polarizability?
(v) Derive the Clausius-Mosotti equation relating polarizability with the permittivity.
(vi) Explain ionic polarization mechanism with necessary mathematical tools.
(vii) Give reasons for non-occurrence of orientational polarization in polar molecules under high frequency electric fields.
(viii) What are the parameters on which orientational polarizability is dependent? Explain with necessary derivation.
(ix) Explain interfacial polarization mechanism.
(x) Establish that polarization is frequency dependent.
(xi) Upon which parameters, does the power loss in capacitor depend?
(xii) Briefly explain the breakdown mechanisms in solid and gaseous dielectrics.
(xiii) What is ferroelectricity and piezoelectricity? What are similarities and differences between ferroelectricity and piezoelectricity?
(xiv) Name the field of application of different types of dielectric materials.
(xv) In your opinion, how does the polarization mechanism affect in the operation of an electrical system having many components in which polarization takes place during their normal operation? Are the effects same in both the ac and dc system? Explain.

5. Magnetic Materials

(i) Define magnetic dipole moment, atomic magnetic moment and magnetization vector.
(ii) Based on magnetization, differentiate between ferromagnetism, ferrimagnetism, antiferrimagnetism and paramagnets.
(iii) Explain the domain structure of ferromagnetic materials.
(iv) What is magnetostriction?
(v) Explain the magnetization and demagnetization of ferromagnetic materials.
(vi) What is the significance of hysteresis loop? Explain.
(vii) Mention the properties of soft magnetic materials.
(viii) Why ferrites are used for high frequency applications? Explain.
(ix) What is the reason behind use of hard magnetic materials for manufacture of permanent magnets and memories?
(x) Mention common properties of hard magnetic materials.
(xi) What are the common hard magnetic materials? How they are prepared?
(xii) What is the reason behind jerks in magnetization vector during magnetization process?
(xiii) Why pure Fe is not used in manufacture of ac machinery?
(xiv) Which is the most commonly used magnetic material for ac machinery? And, why?
(xv) Differentiate between hard and soft magnetic materials. Suggest which type of magnetic materials to use for the manufacture of power transformer cores and why?

6. Semiconductor Materials

(i) Justify the use of group IV materials as semiconductors. Are all the group IV materials semiconductors? Justify your answer.
(ii) Give properties of intrinsic semiconductors.
(iii) Describe the process of creation of electron-hole pair in intrinsic semiconductors.
(iv) What is the rationale behind assumption that the impurity concentration (either donor or acceptor) in extrinsic semiconductor is equal to the majority carrier concentration in the semiconductor material? Can this assumption be applied in all cases or are there any conditions attached to it? Explain.
(v) Define majority carrier, minority carrier, ionization energy in extrinsic semiconductors.
(vi) What is compensation doping? What are the differences in a n-type of semiconductor with a net carrier concentration (both majority and minority) that is equal to the same in compensation-doped semiconductor? Explain.
(vii) Which of the physical properties in the semiconductor compensation doping will considerably alter? Explain.
(viii) What is electron affinity in semiconductor? Give the reason for having the work function being greater than the electron affinity.
(ix) What are the mechanisms for generation of only electrons or holes in semiconductors? Explain.
(x) Despite having high mobilities compared to that of metals, semiconductors have low electrical conductivities. Give reasons for this.
(xi) Give physical significances of N_c and N_v.
(xii) Starting from $n \approx N_c \exp\left[-\dfrac{E_c - E_F}{kT}\right]$ and $p \approx N_v \exp\left[-\dfrac{E_F - E_v}{kT}\right]$, derive the expression for intrinsic concentration in semiconductor in terms of energy gap E_g, temperature, N_c and N_v.
(xiii) Where does the Fermi energy lies in semiconductors? How it is related to band gap in non-degenerate semiconductors? Explain with necessary derivation.
(xiv) What are degenerate and non-degenerate semiconductors? Does the Fermi energy in semiconductors always lay in the band gap? Give explanation to your answer.
(xv) What is minority carrier suppression in extrinsic semiconductors? Explain.
(xvi) What are the factors that affect most the conductivity of intrinsic semiconductors?
(xvii) Justify that the conductivity associated with minority carrier concentration can be neglected in extrinsic semiconductors.
(xviii) Describe the effect of temperature on resistivity of intrinsic and extrinsic semiconductors. Are the effects identical in both the cases? Give justification to your answer.
(xix) Differentiate between diffusion and drift mechanisms of charge carriers in semiconductor.
(xx) What is the impact of temperature on mobilities of charge carriers in semiconductors?
(xxi) How band bending occurs in semiconductors?
(xxii) Derive Einstein relationship.
(xxiii) What are the trap centers in semiconductors? Explain the indirect thermal generation and recombination mechanism.
(xxiv) How the EHPs generated by photogeneration behave after the source of illumination is switched off? Explain with necessary mathematical derivations.
(xxv) Define minority carrier diffusion length, minority carrier lifetime. How they are related to each other?

(xxvi) What happens when a n-type semiconductor is brought into contact with a p-type? Explain with necessary diagrams.

(xxvii) What is built-in electric filed and built-in potential? What will be the direction of internal field in the vicinity of the junction and why?

(xxviii) How is the built-in potential related to carrier concentrations in the semiconductors?

(xxix) Prove that the depletion width is mostly extended in to the region with lower impurity concentration compared to the region with higher impurity concentration.

(xxx) A junction is formed by joining n-type and p-type semiconductors with respective donor and acceptor concentrations of 10^{16} and 10^{18} per cm^3. How will the depletion region be extended in either region?

(xxxi) What are the factors that mainly affect the width of the depletion region in an abrupt pn-junction? Explain.

(xxxii) Explain with the energy band diagram the forward biased pn junction. Derive mathematical expressions for the same.

(xxxiii) What are the main factors that affect the current through forward biased pn- junction.

(xxxiv) Explain with energy band diagram how the charge carriers behave in a reverse biased pn junction.

(xxxv) What are the factors that mainly determine the magnitude of current through a pn junction? How does the temperature affect the current in reverse biased pn-junction? Can the current due to thermal generation overwhelm the reverse saturation current? Explain.

(xxxvi) What will be the affect of reverse biasing in pn junction on built in potential, internal field and depletion width?

(xxxvii) What is a Schottky junction? How do you understand the term Schottky barrier height? How is the current through the junction expressed during open circuit of the Schottky junction?

(xxxviii) What are the basic differences between Schottky junction and ohmic contacts?

(xxxviii) Expalin the process of formation of Ohmic contact with necessary energy band diagram.

(xxxix) What happens when a metal and an n-type semiconductor are brought into contact with the function of metal being greater than that of the n-type semiconductor? Explain with the energy band diagram.

(xl) Discuss whether doping always increases the conductivity or not.

(xli) A Si wafer has been doped with 10^{17} arsenic atoms per cm^3. Calculate the conductivity of the sample at $300K$. Where will be the Fermi level with respect to the intrinsic Fermi level in Si? Calculate the conductivity of the sample at $400K$. Use graphs wherever required.

(xlii) The sample given in question (xli) is further doped with 9×10^{16} boron atoms per cm^3. Calculate the Fermi level of the sample and conductivity at $300K$. What type of semiconductor will result in?

(xliii) Produce a neat sketch of the dependence of the conductivity on the temperature as $\log(\sigma)$ versus $1/T$ and mark various critical temperatures and other relevant information.

(xliv) Sketch schematically the dependence of electron concentration in the conduction band on the temperature as $\log(n)$ versus $1/T$, and mark the various important regions and critical temperatures. For each region draw an energy band diagram that clearly shows from where the electrons are excited into the conduction band.

(xlv) What is the average number of valence electrons per atom for a pair of Ga and As atoms and in GaAs crystal?

(xlvi) What will happen if Se or Te from group VI are substituted for an As atom in GaAs crystal? Explain.

(xlvii) What will happen if Zn or Cd from group II are substituted for an Ga atom in GaAs crystal? Explain.

(xlviii) Calculate the intrinsic conductivity and resistivity of GaAs at room temperature. The intrinsic concentration, electron mobility and hole mobility of GaAs are 1.8×10^6 per cm^{-3}, $8500 \, cm^2V^{-1}s^{-1}$ and $400 \, cm^2V^{-1}s^{-1}$ respectively at $300K$

(xlix) For the semiconductor in question xlviii, where will be Fermi level with respect to the intrinsic Fermi level if the ionized donor concentration is $10^{15} \, cm^{-3}$? Also calculate the conductivity of the sample. Take the electron and hole concentrations from above question.

(l) Consider an n-type silicon that is heavily doped and the electron concentration in the conduction band is 10^{20} per cm^3. Where will be the Fermi level? Can the expression $n_i^2 = np$ still valid to calculate the hole concentration? What type of semiconductor is this?

(li) A Schottky junction formed by Au and n-type semiconductor based on silicon with donor concentration of 10^{16} per cm^{-3} have a cross-sectional area of $1mm^2$. Calculate the theoretical barrier height from metal to semiconductor if the work function of Au is 5.1 eV and that the electron affinity of silicon is 4.01eV. And, what will be the reverse saturation current through the junction given the experimental barrier height of 0.8eV? Also calculate the current through the junction when a forward bias voltage of 0.3V is applied.

7. Semiconductor Materials Processing

(i) How is the pure silicon material obtained?

(ii) Why silicon needs to be purified?

(iii) What is the reason behind widespread application of silicon in semiconductor materials processing and manufacturing?

(iv) Explain the floating zone method of crystal growing.

(v) How a single silicon crystal is obtained by Czochralski growth method? Explain with a neat sketch.

(vi) Name the mechanisms of introducing impurities to the silicon semiconductor.

(vii) What is diffusion? State Fick's laws of diffusion.

(viii) Describe different diffusion systems. Compare between them.

(ix) Describe chemical reactions for obtaining boron trioxide which will eventually be the source of boron to be diffused in to the silicon semiconductor.

(x) What is the common source of phosphor that is doped in to silicon to form n-type semiconductor?

(xi) What are the common sources of phosphorous pentaoxide, which is necessary for donor diffusion in silicon? Give relevant chemical reactions.

(xii) How arsenic and antimony are obtained, which will ultimately be doped in to the silicon to form an n-type semiconductor?

(xiii) Explain the ion implantation process with a neat sketch.

(xiv) What are the advantages of ion implantation process over diffusion process?

(xv) Compare between diffusion and ion implantation process for impurity doping in to silicon semiconductor.

(xvi) Produce the Gaussian distribution resulting from ion implantation.

(xvii) Define lattice damage and annealing with reference to ion implantation process in semiconductors.

(xviii) How silicon and silicon dioxide are deposited by CVD method from silane gas?

(xix) What is epitaxial growth? What are the most commonly used compounds for epitaxial growth in silicon semiconductor?

(xx) Define photolithography, etchant, and monolithic fabrication.

(xxi) Describe the planar process of device fabrication with necessary sketches.

(xxii) Why metallization of contacts is necessary?

8. Superconductivity

1. What is the difference between perfect conductor and superconductor? Explain how do the electrical, thermal and magnetic properties of superconductors differ from those of normal conductors.

2. Explain the difference between type I and type II superconductors.

3. Explain the term critical magnetic field in a superconductor. How does the critical magnetic field vary with temperature in type I and type II superconductors?

4. What is *Meissner* effect? Explain how *Meissner's* effect is complete for type I and incomplete for type II superconductors?

5. Derive *London* equation and explain the *London* penetration depth.

6. What is coherence length? Derive the relation of coherence length in terms of gap energy and Fermi velocity.

7. What is critical current? Prove that the critical current decreases linearly with the increase in applied field for a wire.

8. What does the equation $B = $ Constant tell ? Is this equation adequate to explain superconductivity?

9. Write a short essay on the application of superconductivity.

10. Give qualitative description of BCS theory. Explain how does it account for superconducting state?

11. Expalin BCS ground state. How is it different from non - interacting Fermions?

Some Common Physical Constants

D

Appendix

Atomic mass unit	amu	1.66054×10^{-27} Kg
Avogadro's number	N_A	6.022×10^{23}/mol
Bohr magneton	β	9.27×10^{-24} J/T
Mass of electron	m_e	9.11×10^{-31} Kg
Charge of electron	e	1.602×10^{-19} C
Mass of proton	m_p	1.67×10^{-27} Kg
Electron magnetic moment	μ_e	9.28×10^{-24} J/T
Proton magnetic moment	μ_p	1.41×10^{-26} J/T
Nuclear Magneton	μ_N	5.05×10^{-27} J/T
Boltzmann constant	k	1.38×10^{-23} J/K
Absolute permeability of vacuum	μ_0	$4\pi \times 10^{-7}$ H/m
Absolute permittivity of vacuum	ε_0	8.85×10^{-12} F/m
Planck's constant	h	6.624×10^{-34} Js
Reduced Planck's constant	$\hbar$	1.055×10^{-34} Js
Speed of light	c	2.9979×10^{8} m/s
Atomic density of Si	ρ	5.0×10^{22} atoms/cm^3
Intrinsic carrier concentration of Si	n_i	1.5×10^{10} cm^{-3}
1 Angstrom	Å	10^{-10} m
1 eV		1.602×10^{-19} J
1exa	E	10^{18}
1peta	P	10^{15}
1tera	T	10^{12}
1giga	G	10^{9}
1mega	M	10^{6}
1atto	a	10^{-18}
1femto	f	10^{-15}
1pico	p	10^{-12}
1nano	n	10^{-9}
1micro	μ	10^{-6}

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Appendix E

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About the Authors

Dr. Pokharel is a Professor of Physics at Institute of Engineering, Pulchowk Campus. He is a Senior Associate of the Abdul Salam International Centre of Theoretical Physics, Trieste, Italy. His academic qualifications include M. Sc. (TU) in Solid State Physics, M. Sc. (UK) in Materials Science and Ph.D. (India) in Materials Science and Technology. He has about 20 years of experiences in research and teaching in undergraduate and graduate levels. He was visiting scientist in 1998 at the Centre for Advanced Technology, Defense Ministry, Indore, India. His research contributions include "Synthesis, Structure and Phase Transition Behaviour of Ferroelectric and Antiferroelectric ceramics as well as Polymers materials. He has contributed more than dozen of research papers in national and international reputed Journals. He has conducted several national and international materials science projects. Under his guidance about half a dozen of M. Sc. (Physics) students have conducted their thesis works.

Mr. Karki is currently working as Lecturer and Program Coordinator, M. Sc. Power Systems Engineering Program at the Department of Electrical Engineering, Pulchowk Campus. He completed M. Sc. in Electrical Power Systems (Hons) in 1995 from Belarussian State Polytechnical Academy, Minsk, Belarus. After the completion of the study in Belarus, he joined Institute of Engineering, Tribhuvan University as a lecturer and taught at Purwanchal Campus, Dharan from 1995 to early 1999. Then he moved to Pulchowk Campus where since then he is teaching at both the undergraduate and postgraduate level.

He has supervised many undergraduate projects and Master's theses at the Institute of Engineering. He was a Guest Research Fellow at Osaka Sangyo University, Japan in the year 2000 and has participated and presented papers at many international conferences. He is member of IEEE, Nepal Engineers Association and a registered professional engineer in Nepal. His research interests include Power System Planning, Operation and Control, Power Sector Restructuring, Distributed Generation, Mini Grid, High Voltage Engineering, Renewable Engineering.

Periodic table of elements

Legend:
- Atomic number — 43
- Atomic mass (mean relative) — (98.91)
- Symbol — Tc
- Melting point [°C] — 2140
- Boiling point [°C] — 5030
- Density [g/cm³], for gases [g/l] (0°C, 1013mbar) — 11.5
- Electronegativity — 1.9
- Radioactive

1 (1A)	2	3 (3A)	4 (4A)	5 (5A)	6 (6A)	7 (7A)	8	9	10	11 (1B)	12 (2B)	13 (3B)	14 (4B)	15 (5B)	16 (6B)	17 (7B)	18 (0)
H																	He
Li Be												B	C	N	O	F	Ne
Na Mg												Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	Lu	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Lr	Rf	Db	Sg	Bh	Hs	Mt	Uun	Uuu	Uub	Uuq		Uuh		Uuo	

6 Lanthanoids

La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb

7 Actinoids

Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No