Nobel Prize for the scientists who made Information Technology a reality

The story of Heterotransistor , Alferov , Smart Devices and Nobel Physics Prize 2000

By Haobam Sachidananda

On December 10 2000,Sweden's King Carl XVI Gustaf will present this year's Nobel Physics Prize to Zhores I . Alferov of the Abram F . Ioffe Physico – Technical Institute , St . Petersburg , Herbert Kroemer of the University of California , Santa Barbara and Jack St. Clair Kilby of Texas Instruments Inc . , Dallas among the other Nobel laureates at the official ceremony in Stockholm . Of them Jack Kilby gets half of the prize money worth 1 million U . S . dollar approximately . Earlier , the Royal Swedish Academy of Sciences had announced that these three scientists were awarded the prestigeous prize for ushering in Information Technology . Thus the significance of their work is obvious and the field focussed here is Modern Electronics with emphasis on Optoelectronics and chip technology . But what is their actual work ?

Background :

Electronics is the study of controlling electricity through the dynamics and physical behaviour of charge carriers in vacuum and matter . Modern electronics uses semicondutors for the purpose .

A semiconductor has conductivity between that of an insulator and a conductor . A particular aspect of Quantum theory , a mathematical frame work , known as the Band theory describes the properties of semiconductors . In a semiconductor , the atoms are arrayed in the form of a crystal lattice with electrons forming valence bond between neighbouring atoms . According to this theory , the outermost electrons of every atom fall into specific energy bands . For semiconductors , there are not much electrons inclined to conduct current in the valance band . A small amount of energy given to a semiconductor boosts some electrons to a higher energy level called the conduction band enabling them to carry current . The energy needed to propel an electron from one band to another is the band gap .Different semiconductors have different band gaps . The conduction of electricity takes place in a semiconductor in two different ways , by extra electrons that do not fit into the valence bands and through holes created by missing electrons in the valence bands . The current carriers , electrons and holes are introduced by adding trace amounts of impurities to the semiconductor material . Such a process is known as doping . Impurities such as phosphorus go into the semiconductor as positive ions each giving up one electron . The electrons so introduced give the N type semiconductor . Other impurities such as boron go into the crystal as negative ions each taking an electron from the valence bond creating a hole . The result is the P type semiconductor . The most important semiconductors are germanium Ge , silicon Si and gallium arsenite GeAs .

In 1947 William B. Shockley , John Bardeen and Walter H . Brattain of Bell Laboratories , New Jersey invented the first transistor . A transistor is the semiconductor valve that could amplify the electric current . In its simplest form it has three metallic contacts on different regions of a specially prepared block of semiconductor . A voltage applied third contact controls the current flow between the first and second contacts . The contact type transistors use the rectifying property of a metal semiconductor contact and junction transistors , the rectifying property of differently doped semiconductors junction . A diode is just the rectifying interface . Here rectification is the process of passing current easily in one direction and resisting it in the opposite direction and amplification is the process of increasing current . They could also function as an electronic switch . Based on these functions they were used for communications and making computers . For these works , Shockley , Bardeen and Brattain were honoured with the 1956 Nobel Physics Prize . All sorts of practical transistors can be grouped into two basic types – field effect ones that are field controlled employing only the majority carriers and bipolar ones that are current controlled relying on both types of charges , electrons and holes . Among different transistors developed , Metal Oxide Semiconductor Field Effect Transistor , MOSFET, finds appeal in the Very Large Scale Integration ,VLSI , circuits .

Subsequent efforts were to increase the mobility of electrons of the semiconducting materials . Negative resistance helps in this regard . Negative reistance decrases current by increasing applied voltage . Impact Ionization Avalanche Transit Time , IMPATT , diodes and Traped Plasma Avalanche Triggered Transit ,TRAPATT , diodes exhibit negative resistance by employing different techniques for delaying of avalanche current . In 1958 Leo Esaki discovered that heavy doping causes tunneling in semiconductors . Tunneling is the quantum mechanical process of crossing a potential barrier with insufficient energy . Esaki diode , a thin junction diode , based on the tunneling effect exhibits negative resistance under low forward biased conditions as the property of junction . A forward biased condition is the condition of connecting the P region of a semiconductor device with the positive terminal of a battery and the N type region with the negative terminal and the reversed biased condition is the other way round . Esaki shared the 19 73 Nobel Physics Prize with Ivar Giaever and Brain D . Josephson for this work . The Transferred Electron Effect dicovered by J. B . Gunn in 1963 showed negative resistance as a bulk property of semiconductors . This resulted in the development of Gunn diode . These new devices could handle microwave , 10^{8} – 10^{10} Hertz , effectively . But a light wave whose frequencies ranges from 10^{14} Hertz to 10^{15} Hertz can transmit a huge amount of information rapidly and efficiently . These can be done through hair thin strands of glass called optical fibers. An ideal light source for the purpose is the Light Amplification by Stimulated Emmission of Light , LASER . A laser produces coherent light , a single frequency , in phase , polarised and directional light . Semiconductor laser using injection current fits the description . Another candidate considered is the Light Emitting Diode LED , based on the electroluminicence phenomenon of generating light by passing an electric current through a material under an applied electric field whose particular feature is the narrow range of wavelengths in the spectrum . Optical waveguides using the property of internal reflection carry light signals in the optical fibers . Semiconductor photodetectors are also employed for detecting light signals . Heterostructures make all these optoelectronic devices pssible .

Present Work :

As far back as 1951 , Shockey suggested the use of heretero junction transistors . In the mid 1950's German born Kroemer of the University of California , Santa Barbara developed the theory of such transistors . He even introduced the concept of graded heterostructure . He had earlier worked on the theoretical aspect of Gunn effect . To be precise he independently identified the cause of Gunn effect as negative differential resistance . But he is better known for the graduate level text book ' Thermal Physics ' which he coauthored with famous Charles Kittle to the student community . He also worked at Radio Corporation of America , RCA , New Jersey . It was left for Alferov at the Ioffe Physico – Technical Institute , St . Petersburg in the late 1960's to carry out the pioneering work of creating ideal semiconducting hetrostuctures and injection lasers based on them operating in the continous wave CW mode at room temperature . In 1971 , Alferov extended the range of semisonductoing materials to quaternary solid solutions of $A^{III} B^{V}$ compounds for preparing high quality heterojunctions. Studies reveal that the GaAsP solid solutions with narrow band composition suitable for creating LEDS .During 1975 –76 Alferov fabricated the first visible injection laser based on InGaAsP/GaAsP heterojunction. Besides , heterojunctions dramatically improved the performance of practically all the basic semiconductor devices . Heterophotoconvertors based on $A^{III} B^{V}$ compounds ensures a high conversion efficiency for solar cells generating electricity from sunlight . An excellent book " Semiconductor Heterostructures : Physical Processes and Applications " edited by Alferov himself gives a good technical account of the subject .

(to be contd.)

Nobel Prize for scientists who made IT a reality-II

By Haobam Sachidananda

A hetrojunction is the junction formed between two chemically different semiconductors . It is taken to be ideal if the density of interface states for recombination and trapping centres is negligibly small at the interface . If the two semiconductors have the same type of conductivity , then it is called an isotype heterojunction . Othewise , the heterojunctions are ansisotype . Also the heterojunction can be either abrupt or graded at the interface . The working of a heterojunction is quite subtle . The Anderson model describes the energy band diagrams and electrical properties of ideal heterojunctions quite accurately . In a heterojunction there are discontinuities at the interface in both the valence and conduction bands , their margnitudes being constant for a given pair of materials . These are the centres of all actions . Due to these discontinuities the potential barriers for electrons and holes are different causing uinidirectional injection in heterojunctions . At a certain value of the forward bias , the injected carrier density exceeds the equilibrium carrier density . This is kwown as the superinjection effect . Both the unidirectional injection and the superinjection effect drmatically improves the parameters of semiconductor devices . A specific feature of recombination process known as the electron confinement effect exhibited in heterojunctions by the dicontinuities localizes Non Equilibrium Charge Carriers NCC in the narrow gap region of the heterostucture between two wide gap regions . The possibility of increasing the concentration in the active region of a double heterostructure DH makes heterojunction devices sources of spontaneous and coherent radiation . Again the band discontinuities make the injected carriers posses high kinetic energy in both isotype and anisotype abrupt heterojunctions ensuring the heterojunction of the hot carriers injection with a practically monoenergetic low spectral energy . Also carriers tunnel inside a band in abrupt hetojunctions lowering the injection process efficiency . At an intermediate stage in reverse –biased heterojunction the intraband tunneling of minority carriers lowers the reverse current. This effect is used for designing high temperature diodes with low reverse currents . The break down caused by the difference in the diaelectric constants , the ionization threshold energy and impact ionization create electron – hole pairs in an anisotype abrupt heterojunction. This makes the lowering of necessary voltage possible for avalanche multiplication to start . The manufacturing of high quality avalanche photodiodes underlies in this effect . The possibility of merging the light – absorption region and the region of NCC separation makes heterojunction favourable for the manufacture of highly effective high – speed photodiodes . The band gradient in graded heterostructures prevents the sensitivity in the short wave range from dropping by keeping the velocity at which the carriers leave the surface considerably higher than the surface recombination velocity and reduces losses caused by recombination in the bulk by making the carrier transit time considerably shorter than the carrier lifetime . At high levels of illumination the NCC concentration exceeds the majority carrier concentration in graded heterostructures . So there is the prospect of considerably increasing the effeciency of solar energy converters manufactured from graded heterostuctures in conditions of high illumination levels .

Heterojunctions formed from materials with close lattice constants behave like the ideal model . A particular pair of semiconductors $A^{III} B^{V}$ obtained by combing elements of column III and column V of the periodic table viz , GaAs and aluminium arsenide AlAs mixed in any porportion x , $AlGa_{1-x}$ As alloy serve the purpose . Each new type must have a direct band structure and give a wider spectral range . The search for newer types led to quaternary compounds $A_x^{III} B_{1-x}^{V} C_y^{III} D_{1-y}^{V}$, InGaAsP solid solution . A solution is the homogeneous substance that has a continuously variable composition over certain limits . To create heterojunctions on the bases of quaternary compounds , lattice – match series of their compositions should be used . All the compounds in each series have the same lattice constant to a proper choice of the parameters x and y . However , other physical parameters of these compounds especially the band gap are different for different compounds in a series . Usually the value of band gap and lattice constant are predicted by a fourth degree interpolation of the data known for binary compounds InAs , GaAs , GaP and In P etc . and the ternary solid solutions InGaAs , InGaP , InAsP , GaAsP etc. taking in to account the mixing effects inherent in quaternary compounds . The study of phase equilibrium gives an accurate control of the solution composition in InGaAsP quartarnary system . The temperature dependencies of the interaction parameters are obtained by processing experimental data on liquidus and solidus isotherms of ternary systems . Under real conditions of epitaxial growth , the unavoidable supercooling of the liquid phase disturbs the thermodynamic equilibrium of the system . The situation gets further worsened by the thermodynamic instability of the binary substrate in contact with the multicomponent liquid phase . Then the system goes over to the quasiequilibrium state after forming a transition layer in equilibrium with the initial liquid phase on the substrate surface . The isothermal growth method solves the problem by obtaining 1 . 2 m m thick layers of solid solutions with a constant composition over the entire thickness of the layer . The layer and substrate system is extremely sensitive to temperature variations . At a certain critical mismatching of the lattice parameters , missfitting dislocation MD appear in the expitaxial layer . These dislocations serve as the centers for nonradiative recombination and their presence is indicated by the dark lines in the lumination pattern of the material decreasing the quantum yield of luminicence . The temperature at which epitaxcy is carried out is essential to obtain layers free from MD's lattice matching as MDs are generated much more easily at higher temperatures than at room temperature . The greater the lattice mismatching between the wider is the heterointerface profiles .

By this time , another development had taken place . The first step in the direction was taken by Jack Kilby at Texas Instruments Inc , Dallas . In 1958 – 59 he successfully built an integrated circuit , IC . An IC is the miniature circuit on a small piece of semiconductor material called chip where the components – resistors , diodes and transistors - are an integral part . It consisted of a silver of germanium with five components linked by wires . The tiny wires linking the components and power supply were simply soldered on and the whole thing was held together by wax . It measured two – fifths of an inch . Just to demonstrate its potential , Texas Instruments first built a computer using 587 ICs for the U . S . Airforce . Kilby is a prolific inventor and has about 60 patents to his credit . He is also the co – inventor of the pocket calculator . ICs made minicomputers smaller , more reliable and inexpensive . This led to the third generation of computers . For the ever increasing processing power of computers , the need raised from the Small Scale Integration , SSI , chip consisting of less than 12 integrated components to the Very Large Scale Integration ,VLSI , chip which consists of more than 1000 integrated components . A monolithic IC in which the components are part of one chip is found suitable for the purpose . Nonideal heterojunctions find applications in monolithic ICs . They are produced by using Photolithography , the process by which a microscopic pattern is transferred from a photomask to a material layer in an actual circuit . The whole process is done in clean rooms where the air is constantly filtered and workers are swathed in surgical type garb as a single speck of dust ruins a chip . Another breakthrough occurred when a young electronics engineer , M . E . Ted Hoff at the then newly formed Intel Corporation , Santa Clara invented the first microprocessor by placing most of the arithmetic and logic circuits on one chip of silicon which contained 2, 250 transistors in an area barely four millimetres long and three millimetres wide . Intel's latest microprocessor Pentium 4 packs 4 . 2 million transistors for performing 8 . 4 billion operations per second . These are the features of the present fourth generation computers , the popular personal computer PCs .

Unlike conventional devices , all the smart devices practically make use of ICs and optoelectronic devices . An electronic watch depends on LEDs for its working . Cell phones are possible because of ICs embedded on it . There rae intelligent microwave ovens and washing machines etc . as the embedded ICs do the logic workings . In compact disc CD and Digital Versatile Disc , DVD , players a tinysemiconductor laser reads the digital data recorded on the disc with a semiconductor photodetector . The bar code reader , actually a scanner uses low power semiconductor lasers . In a laser printer , a semiconductor laser digitally controlls the minute beam for creating a stored image in the form of charged areas on a rotating drum coated with a photoconducting material . A semiconductor works in a similar fashion for the photocopier.

Lastly a few words about the 2000 Nobel Physics Prize needs mention . This year's Nobel Physics Prize awarded jointly to Kroemer , Alferov and Kilby is the third one for a major work in the field of electronics . The work on heterostructures by Kroemer and Alferov also formed the basis for studying Quantum Hall Effect that brought two Nobel Prizes in 1985 to Klaus von Klitzing and in 1998 to Robert B . Laughlin , Horst L . Strormer and Daniel C . Tsui . Really the award brings to the fore their work unknown to the common people . Alferov says that the award to him is a tribute to the Russian Physics . Definitely , it will definitely boost the Russian Physics emerging after the breakup of the earnestwhile Soviet Union . . In Russia , the economic crisis is so acute that a fusion scientist is reported to be paid less a american big company clerk . Moreover , many anti – science trends had cropped up in this backdrop . **Concluded.**