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Semiconductor Switching Devices· ·Future Trends

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ABSTRACT

A variety of semiconductor devices and circuits have been successfully developed using conduction properties of electrons and holes in a number of elemental and compound semiconductors. Carriers confinement in a potential well, formed out of a thin layer of lower band gap material sandwitched between two layers of a higher band gap material, has been extended from one to two and three dimensions. Resultant of two-dimensional carrier sheet, quantum wire and quantum dot having discrete energy levels arising out of quantisation are being presently explored for possible device applications. A number of devices have been fabricated using resonant tunneling across a thin potential barrier. This has opened up several newer possibilities of using such structures for various electronic and optoelectronic devices and circuits applications as tunneling is relatively faster than conduction process. While looking into the interband tunneling between two quantum dots, possibility of a single electron switching has also been examined carefully. The idea of a single electron switching is conceptually being extended from quantum dots to molecules and atoms ultimately. Simulations based on transmission of electrons through a chain of molecules and atoms have shown that tens of THz speed and functional device density 10^{12} devices/mm^2 are possible with such schemes. Devices based on atom relay transistor (ART) will be ultimate in its performance of switching speed. A brief on present-day situation followed by future proposals of fast switching devices for information electronics has been discussed.

1. INTRODUCTION

Energy band structure of a perfectly periodic semiconductor lattice establishes transport properties of charge carriers in terms of band gap and effective mass. Mobility and saturation-limited drift velocity are manifestations of charge carrier interaction with lattice vibrations and imperfections. Performance of these devices are continuously being improved by suitably modifying the corresponding band structure-dependent properties. Replacement of regular periodic lattice by superlattice, addition of more species in the unit cell and generation of strains in an appropriate form, are some of the approaches to change the band gap and effective mass. In another approach, carriers mobility has been enhanced by transferring them from a higher band gap layer to a lower band gap intrinsic layer across a heterostructure, where impurity scattering is avoided. This has led to fast growth of a family of high electron mobility transistors (HEMTs) during the last decade. Using novel device structures based on nanostructure fabrication, single electron and hole transitions have been experimentally confirmed.

1. SEMI-CLASSICAL CHARGE CARRIERS

In a monocrystalline solid of perfectly periodic lattice, electrons have well-defined energy band

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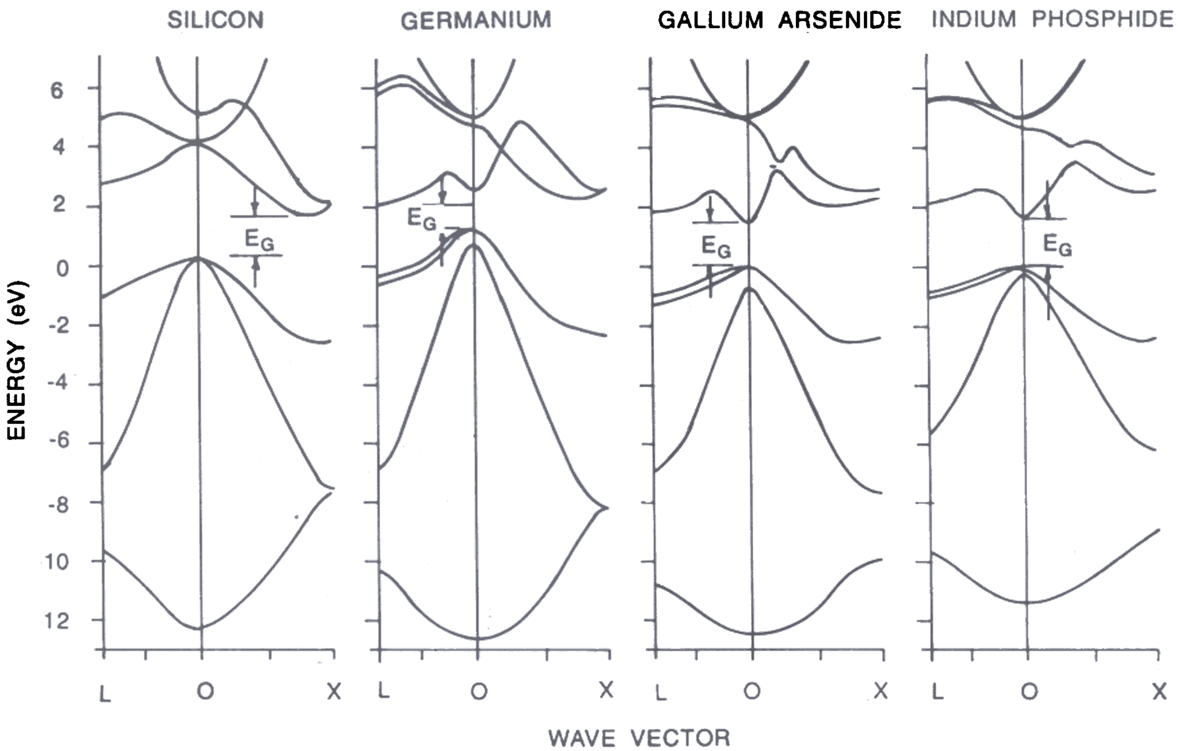

Figure 1. Calculated energy band diagrams of *Si, Ge, InP* and *GaAs*

description[1]. In the form of a perfect-based semiconductor lattice, conduction and valence band energy *vs* wave vector relationships for all relevant semiconducting materials, have been studied. Energy band diagrams of a few commonly used semiconductors are given in Fig. 1. Electrons and holes in semiconductors are attached to a finite effective mass, which is related to the corresponding band gap. Imperfections, which are unavoidable in a practical situation in the form of lattice defects, impurity atoms and lattice vibration phonons act like scattering centres. Movements of the conduction electrons are affected by these imperfections giving rise to a finite mobility and drift velocity *vs* electric field relationship[2] as shown in Figs 2 and 3. Figure 3 shows that in almost all known semiconductors, drift velocity of electrons and holes saturate to approx. 10^7 cm/s. Semi-classical nature of electrons, in materials like *Ge, Si, GaAs, InP* and many more compound semiconductors, has been used to realise unipolar and bipolar devices for a large number of applications used in discrete and integrated forms.

Injection of charge carriers over a potential barrier can be considerably influenced by slight change in the barrier height due to exponential dependence of the current on barrier potential. This concept has been used to obtain amplification and switching in bipolar transistors. In unipolar case, flow of charge carriers in a channel is affected by a transverse electric field applied through a gate electrode. Gate may be separated from the channel by a high quality insulator, *p-n* or Schottky junction. Such devices, known as metal oxide semiconductor transistor (MOST), junction field effect transistor (JFET) and metal-semiconductor field effect transistor (MESFET), respectively show very fast switching characteristics. In these devices, the charge carriers move with almost saturation-limited drift velocity and the overall channel length is made extremely short. Keeping aside the practical limitations associated with the formation of suitable structures in the above cases, the limitations due to charge carrier transport properties are the ultimate restrictions. These are to be taken care of while improving the performance

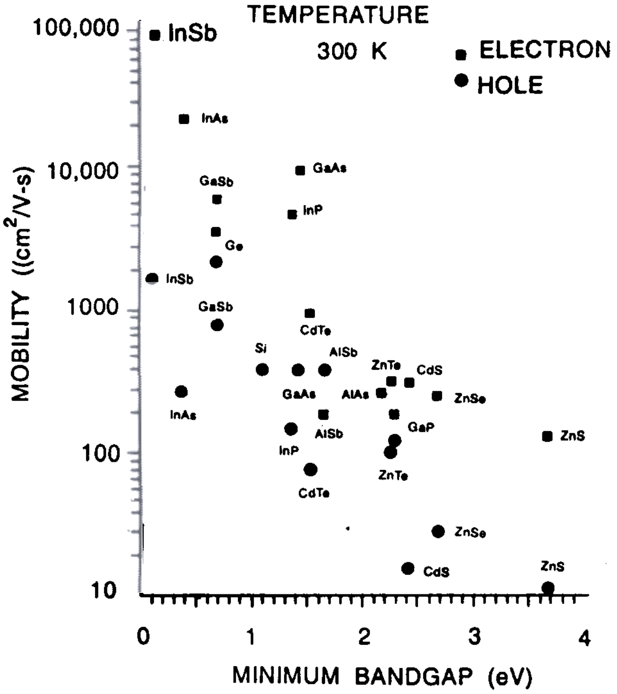

Figure 2. Room temperature electron and hole mobilities in a number of commonly used semiconductors.

of such devices. For example, saturation-limited velocity, which is almost fixed at 10^7 cm/s, is one such restriction. Similarly, mobilities of the electrons and holes in most of the semiconductors are only related to effective masses, which are generally not much different from free-electron mass except in few cases. Therefore, some other mechanism of improving upon the transport properties of the charge carriers should be exploited for extending the performances of such families of devices and circuits to a state better than the present one.

By improving the overall material quality and structure formations in device processing, impressive performances have been achieved in cases of bipolar and unipolar devices. Switching speeds in the range of picoseconds, gate length of the order of 50 nm in MOST and extremely dense VLSI circuits are the results of such improvements[3]. In case of high electron mobility transistor (HEMT) devices, 1.2 dB noise figure at 94 GHz and cut-off frequency above 200 GHz have been evidenced[4]. Discrete devices and integrated circuits have been used in realising very high performance systems in

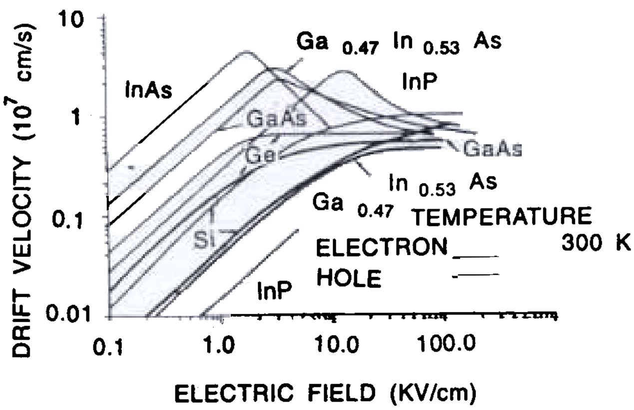

Figure 3. Drift velocities of electrons and holes as a function of electric field in a number of commonly used semiconductors at 300 K.

various fields of electronics. Materials growth has matured to the extent that nonatomic layer epitaxial growth are realised in molecular beam epitaxy (MBE)[5] and atomic layer epitaxy (ALE)[6] techniques on one hand and 500 mm diameter *Si* wafers are produced commercially for various applications on the other. Almost zero-defect density bulk crystals are available for device and circuit fabrications.

2. BAND STRUCTURE MODIFICATIONS

First step towards modification of energy-band diagram of a semiconductor was to change the lattice periodicity by superimposing another periodicity over the basic one. For example, one could take alternate layers of two types of semiconductor lattices A and B, at regular interval, to approximate a situation similar to AB semiconductor lattice. Such possibilities could be many and accordingly, their band structure could be estimated using well-known Kronig-Penny model[7]. These synthetic lattices do possess additional features and are known as superlattices. Effects[7] may be realised by choosing appropriate constituent semiconductors in binary, ternary, quaternary and more complex forms as shown in Figs 4 and 5. In superlattices, effective mass and band gap can be modified to suit different requirements. For example, superlattices based non-alloyed ohmic contacts[8] are being investigated for quantum effect compound semiconductor devices. High temperature

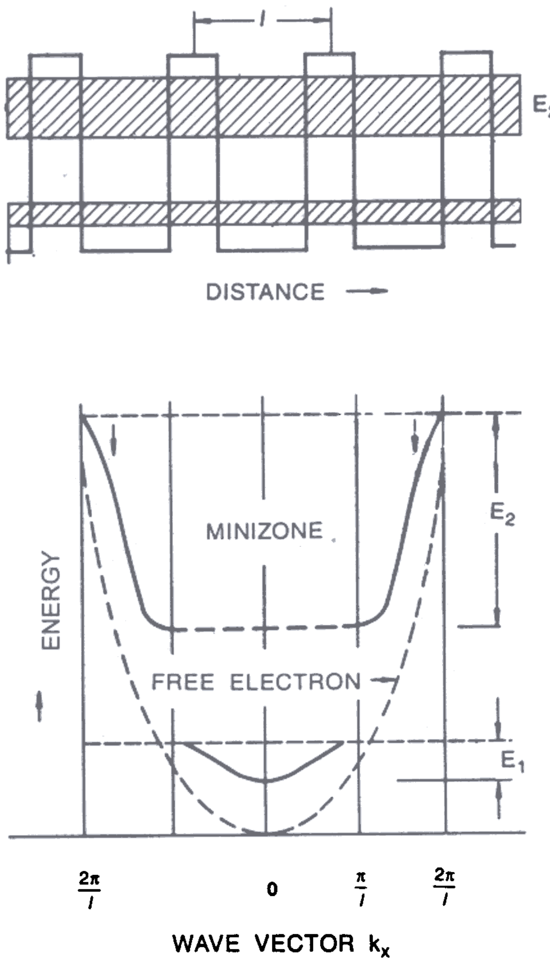

Figure 4. Formation of superlattice: (a) involving two materials having different band gaps and period of l, (b) allowed energy states appear in mini zone.

annealing involved in conventional ohmic contacts are eliminated in such cases as it may be detrimental to the quality of very thin channel and other layers with sharp doping profiles. Similarly, donor and buffer layers in HEMT structures made out of superlattices[9] are more effective and result in superior device performances. Problems like presence of DX centers and losses due to alloy scattering are almost absent in such structures.

Second possibility is to use more than one compatible species in a unit cell and thus modify the band structure. A number of alloy semiconductors with varying molar concentration of a particular species were used to tailor the band gap. Band gap engineered material families are, now-a-days, being explored to develop optoelectronic devices and circuits, where different band gap materials are required to tune the device activity to a specific wavelength of radiation. A number of binary, ternary and quaternary semiconductors have been studied in this context. Lattice constants, band gaps and lattice matching with different types of substrates for a number of such compound semiconductors are summarised[10] in Fig. 6.

While growing epitaxial layers of one material on the substrate with slightly different lattice constant, strains are generated up to certain thickness. In case, growth is continued beyond the said critical limit, lattice defects are generated to take care of the excessive strain. As a result of this limitation, only epitaxial layers below critical thickness limit, are actually usable for device applications. Such strained layers have altered lattice constants due to compressive and tensile stresses as shown in Fig. 7. The energy band structure of the strained layer is considerably modified[11]. In some cases, energy band degeneracies are lifted and different holes energy bands get separated from each other accordingly. Such strain-generated modifications have already been used to realise a number of electronic and optoelectronic devices. Some experimental results have indicated that strained epitaxial layers exceeding critical thickness limits may also be used for device applications in some cases. Presence of lattice defects do not affect carriers transport properties to that extent. Such strained layers, known as pseudomorphic layers, were initially thought to be risk due to in-built tendency of relaxation with time. But, this fear has been proved false in recent reliability experiments. Reasonably, reliable devices are being marketed using pseudomorphic HEMT and laser structures.

Pseudomorphic growth of *InGaAs* on *GaAs* substrate has been used to realise HEMT devices with better properties[12] than those based on *GaAlAs-GaAs* combination. For exploiting full potential of *InGaAs* as channel material for HEMT, one requires high mole fraction of *InAs*. But increase in mole fraction of *InAs* in *InGaAs* reduces the critical thickness limit of pseudomorphically

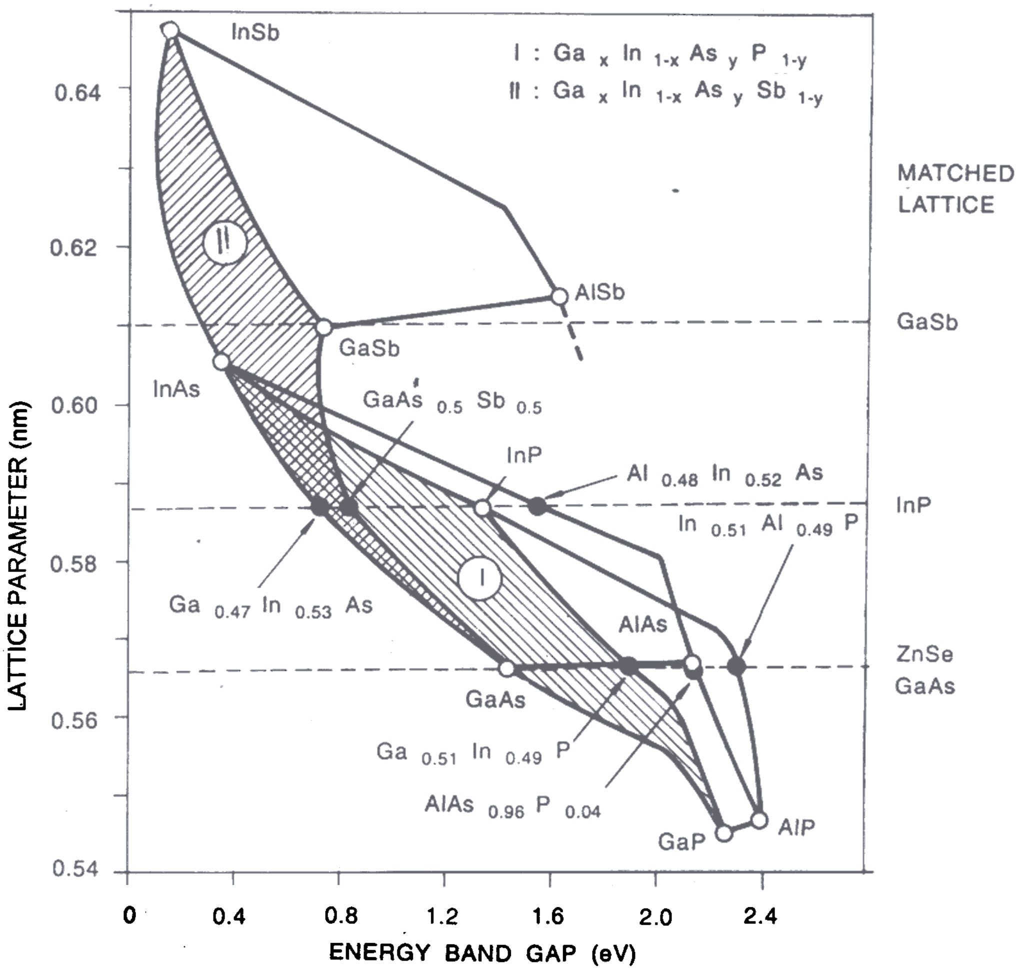

Figure 5. Schematics of different combinations of three species A, B and C to realise possible types of superlattices

grown layer on *GaAs*. Therefore, an alternative of growing *InGaAs* on *InP* substrate than that on *GaAs* was explored for HEMT realisation with better millimeter wave properties. Lattice matching occurs for higher mole fractions of *InAs* in *InGaAs* on *InP* substrate as compared to that on *GaAs*. HEMT devices have been fabricated successfully up to 0.8 mole fraction of *InAs* in *InGaAs* on *InP*[12]. This shows that pseudomorphic growth can be used to get improved characteristics of HEMT devices by taking appropriate combination of active layer and substrate materials.

3. QUANTISATION HELPS

When a higher band gap material forms a heterojunction with a lower band gap material, a triangular potential well is formed on the lower gap side as shown in Fig. 8. This kind of situation is expected to transfer the electrons from the higher band gap side due to favourable barrier structure. These charge carriers, so transferred, may not see the parent donor sites but rather move freely in the lower band gap material as schematically shown in Fig. 9. If the lower band gap material is of high quality and intrinsic type, impurity-scattering losses could be minimum and as a result the mobility of such electrons could be enhanced considerably. Such situations have been studied using Poissons and Schrodinger equations for potential variation and electronic states in potential barrier, respectively. It has been concluded that electrons do transfer to lower band gap side over a distance of 10 nm across the potential well as a result of one-dimensional quantisation[13]. By putting a metal gate at appropriate distance and doping the higher band gap material to a sufficient

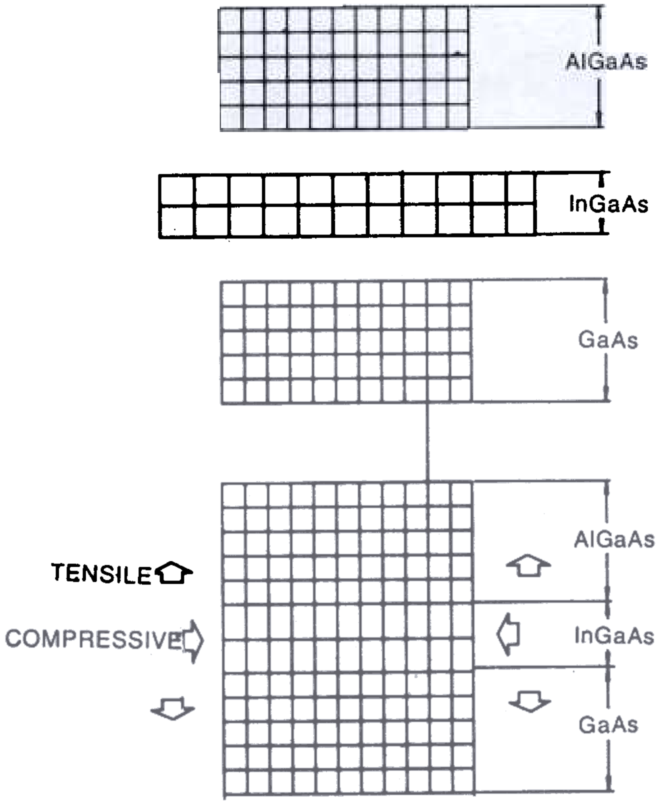

Figure 6. Lattice constants, energy gaps and possible alloy semiconductors having lattice matching to *GaAs*, *InP*, *GaSb* and *ZnSe*.

level, very high sheet carrier density with improved mobility has been obtained in the channel. The generic name of this phenomenon is called selective or modulation doping and field effect device based on this effect is known as high electron mobility transistor (HEMT) or by many other acronyms, e.g. TEGFET (two-dimensional electron gas FET), HFET (heterostructure FET) MODFET (modulation-doped FET and SDHFET (selectively-doped heterostructure FET) used in literature. Many designs of the device have been worked out in the last decade to arrive at an optimum combination of higher and lower band gap materials, doping in the higher band gap material and Schottky gate formation at the higher band gap material. As a result of all these studies, high frequency HEMT devices are now available up to 100 GHz. Extremely low noise, high gain, high power and larger bandwidth characteristics of amplifying devices have been realised with very impressive performances in discrete and integrated forms. Noise properties of some of the experimental[12] devices are summarised in Fig. 10.

Schrodinger equation solutions of an electron in one, two and three-dimensional potential wells are available in modern literature. Discrete energy levels arise out of quantisations in the above cases. Interaction between two potential wells separated by a thin barrier layer presents interesting situation[14], where tunneling can take place from one well to the other, specially when two energy levels are aligned as shown in Fig. 11. Tunneling phenomena, being faster than drift/diffusion-related transport, is expected to result in faster devices in general.

One-dimensional potential well is realised by sandwitching a thin layer of low band gap material of few nanometer thickness in between two thick layers of relatively large band gap semiconductor. MBE, where single atomic layer deposition is easily possible, helps in realising one, two and three-dimensional quantum wells.. These structures are known as charge carrier sheet, quantum wires and dots. How these structures can be realised is shown in Fig. 12. Discrete energy levels of electronic states and their possible transitions have been used to realise a whole family of optoelectronic devices and circuits[12]. Inter-well transition due to quantum mechanical tunneling across a thin barrier has been used to realise bulk negative differential conductivity situation[15] similar to Gunn effect but with more flexible control on resultant I-V characteristics as shown in Fig. 13. Such devices have produced oscillations and switching at very high frequencies and speeds, respectively.

Resonant tunneling devices[14] are extremely attractive as high speed devices but their only drawback is the lower operating temperature. Interlevel separations, if nearer to kT, is completely smeared off. This becomes a major design criteria of such devices when constituent component semiconducting materials are to be chosen for a given combination. Room temperature operations are possible[14] when suitable semiconductors are chosen for quantum well realisation.

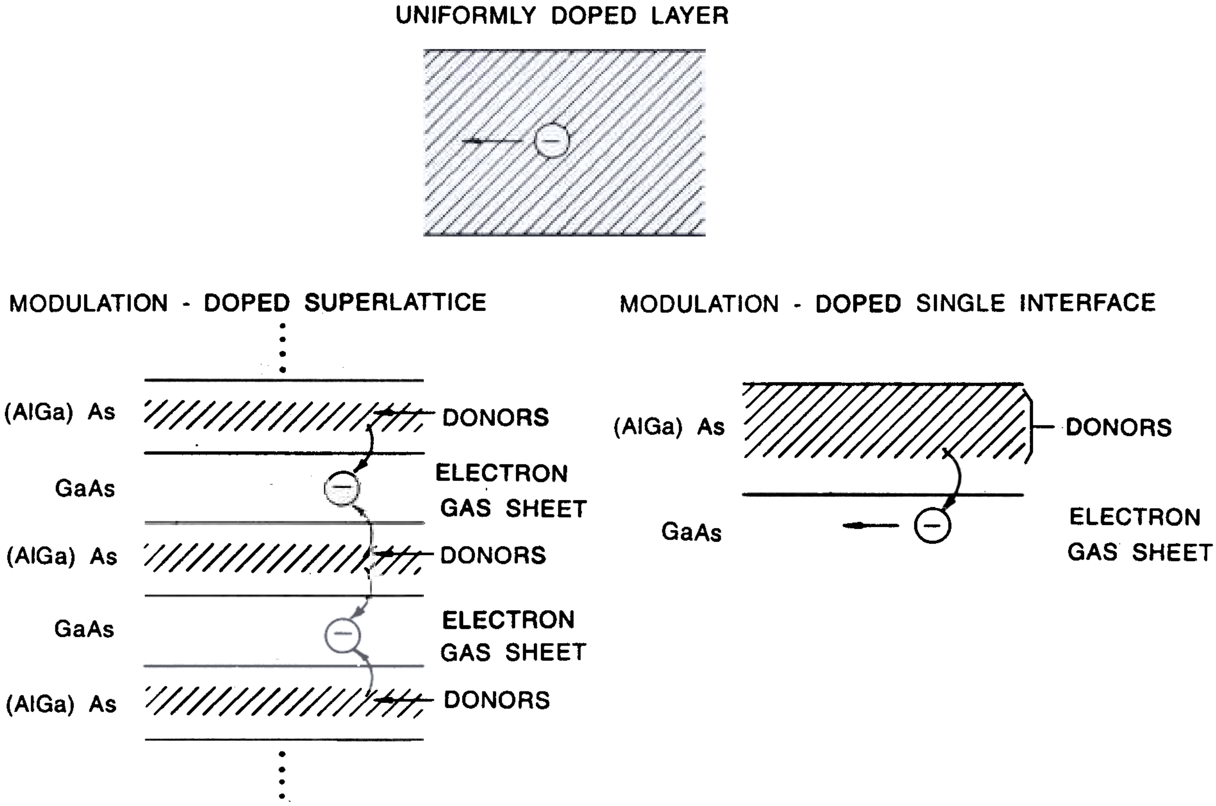

Figure 7. Pseudomorphic growth of *InGaAs* in between *GaAs* and *GaAlAs* gives rise to tensile and compressive stresses in *InGaAs* layer. This leads to modification in energy band diagram.

4. SINGLE ELECTRON TRANSPORT

Electron population in a quasi-isolated island of nanometer dimension can be changed by one unit if total associated capacitance is extremely low and resistance is higher than quantum resistance[16-17] This phenomena is known as single electron transition. Now actual device structures have been realised, where current-voltage characteristics have distinctly shown single electron transport. Generally, due to large capacitance associated with such structures, this effect also known as Conlomb blockade and Conlomb repulsions, is not observed even at low temperatures. However, with the present level of success in nanofabrication, more and more experimental devices are showing such effects clearly. Initial single electron transition experiments have used[18] very small metallic islands separated by thin insulator. Various techniques[18-21] have been suggested to fabricate these structures involving *Al-Al*$_2$*O*$_3$*-Al*, *Pt-Al*$_2$*O*$_3$*-Al*, *Cr-Cr*$_2$*O*$_3$*-Cr* and *Au-Pd*. Few nanometer size clusters are now possible to fabricate under certain conditions and associated capacitance has been estimated to be a fraction of *F* atom. Some authors have used scanning tunneling microscopy[19] to investigate the current-voltage characteristics showing Conlomb

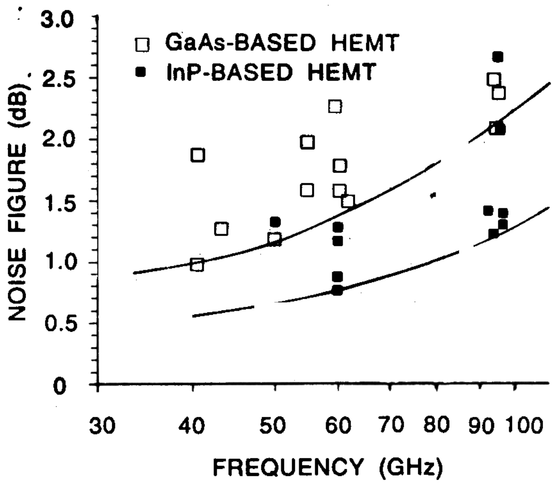

Figure 8. Formation of a triangular quantum well on *GaAs* side in a modulation-doped *AlGaAs-GaAs* hetero-structure.

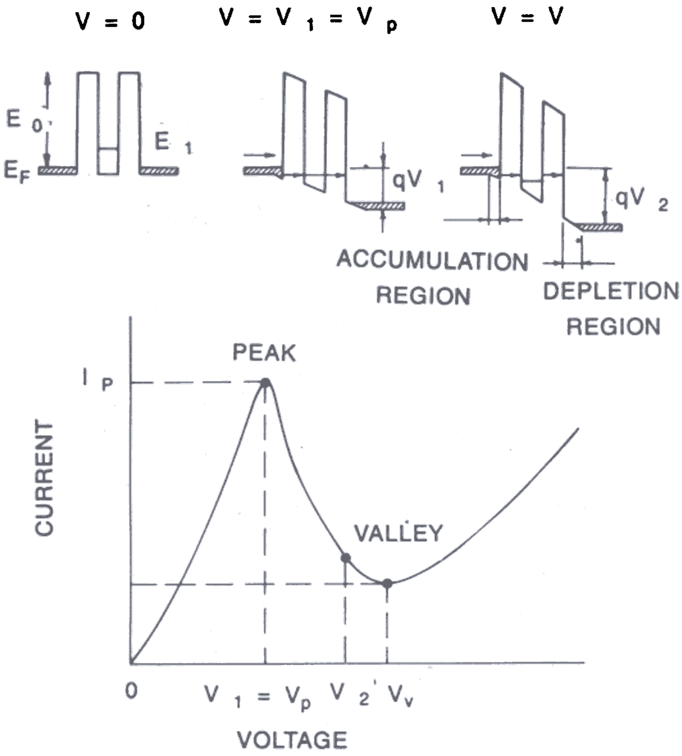

Figure 9. Schematics of electron transfer from higher band gap material to lower band gap material in a modulation-doped single and multiple hetero interface.

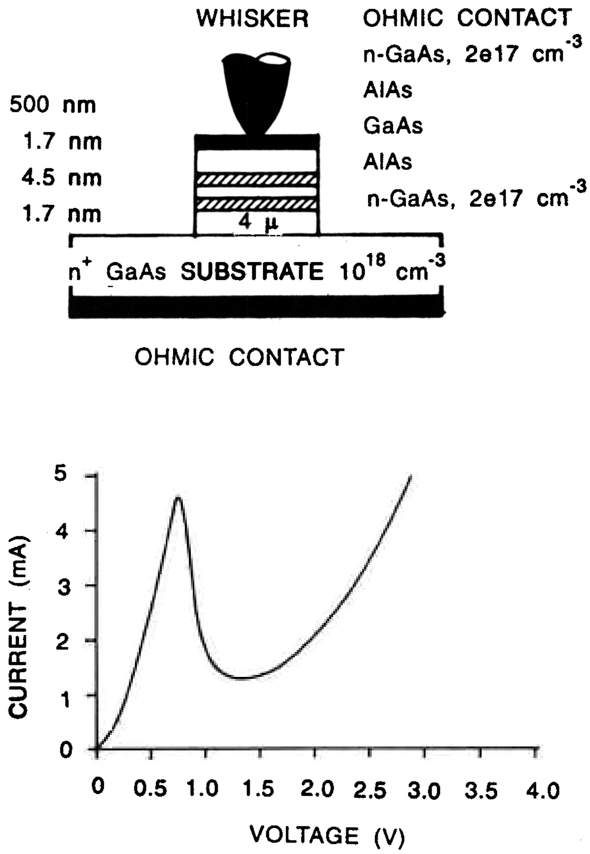

Figure 10. Experimental results of noise figures obtained in *GaAs* and *InP*-based HEMT devices.

blockade effect clearly at lower temperature as shown in Fig. 14. There are evidences to this effect noticeable even at room temperature.

In another attempt[22], two-dimensional electron gas (2-DEG), realised at a heterointerface, has also been used to show single electron effect at low temperature as shown in Fig. 15. With the help of biased gates of smaller dimensions, various experimental conditions have been achieved to lead to single electron transport in different 2-DEG structures. In an alternative approach[23], *Si* on insulator type of structures were employed to observe single electron and hole transistors at 110 K. Drain current oscillations with gate bias clearly show the presence of single carrier transport, which is ideally suited for actual circuit fabrications. Steps involved in such single electron and hole transistor fabrication are shown in Fig. 16.

Room temperature operation of single electron transistor[24] (SET) has been observed using STM for fabricating TiO_x zone defining *Ti* island of 30 x 35 nm^2. Conlomb staircase of 150 mV period was observed in current-voltage characteristics of such a device. Realisation of this type of device shows great promise for future applications of SET's in actual circuits. Schematics of device fabrication steps are shown in Fig.17.

A number of applications of SET have been proposed[16,17,25,26], besides most conventional one i.e. single electron logic, where ultimate fulfilment of the nanoelectronics dream will be realised. Standard DC current source supersensitive electrometry (10^{-4}eV/Hz charge resolution), detection and imaging of infrared radiation are some of the areas where single electron-based device structures find attractive uses. Because of present limit of defining patterns up to 30×30 nm^2, some of the applications are not yet fully exploited. However, with improvement in nanofabrication

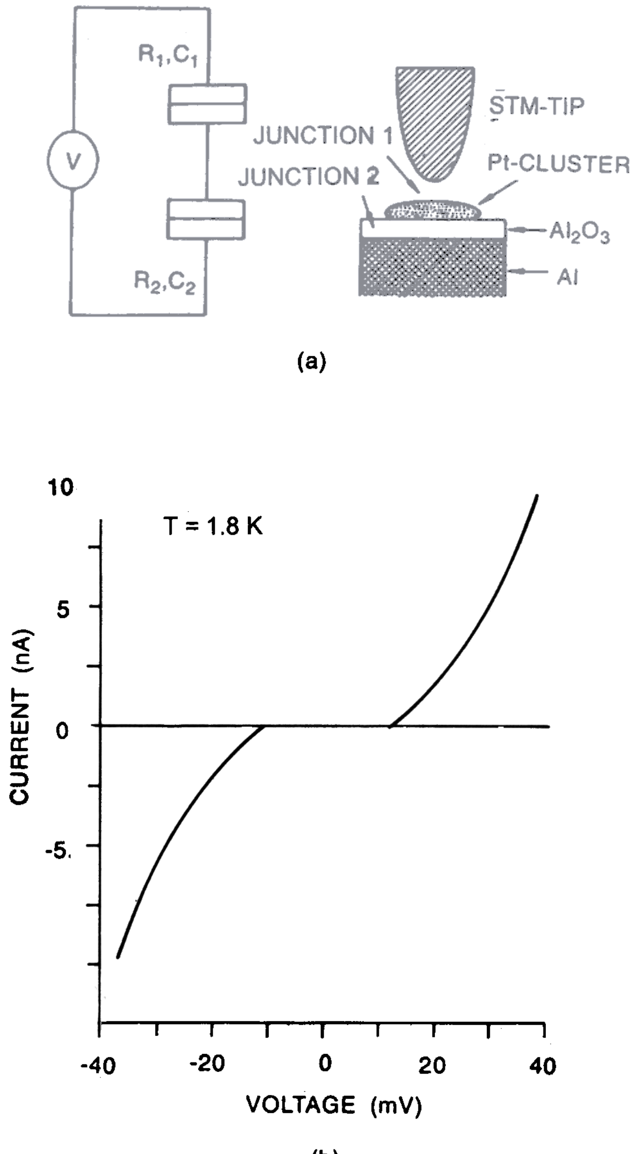

Figure 11. Schematics of interband resonant tunneling and the resultant current-voltage characteristics.

techniques, more attractive application areas will open up in near future. Single electron phenomena has real ultimate potential in switching devices.

One of the major problems being faced at present in the realisation of SET effects in islands is the presence of fractional offset charges on such structures. Moreover, offsets on a number of such islands have been noted to be random in nature. Probable causes are due charged defects in the neighbourhood of the conductors or due to different work functions of the different metal crystal faces.

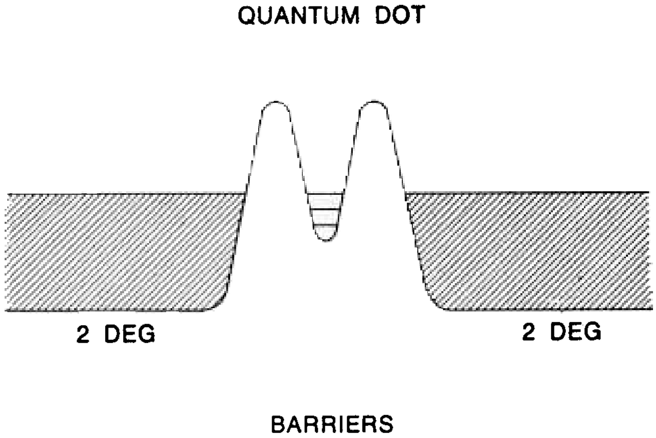

Figure 12. Three, two, one and zero dimension electron gas representations with corresponding density of states.

Offset charges on the islands perhaps give rise to 1/f noise leading to circuit stability problems. A systematic study of these problems are needed to resolve these issues by fabricating better and appropriate structures.

5. WHY NOT MOLECULES & ATOMS ?

Recent progress made in the direction of nanofabrication of structures in metals and semiconductors and systematic study of their transport properties indicate the possible use of molecules and ultimately atoms for single electron transitions for switching. Before the availability of STM, the area of molecular electronics, was explored for possible use in switching. But due to difficult access to the large size molecules and slow switching speed associated, it was not persued further[25]. However, with the help of STM, it is now possible to manipulate individual molecules for different types of applications. A conceptual scheme[25] involving polyacetylene and polyethylene as conducting and insulating molecules respectively, can be considered for tunneling of electrons from polyacetylene molecules through polyethylene (Fig. 18). Simulation studies regarding electron density distribution for such a system suggest that a three-terminal device with 10 THz speed, is possible using such molecules. In this connection, a novel micromachine STM (μ-STM) has been suggested for manipulation of

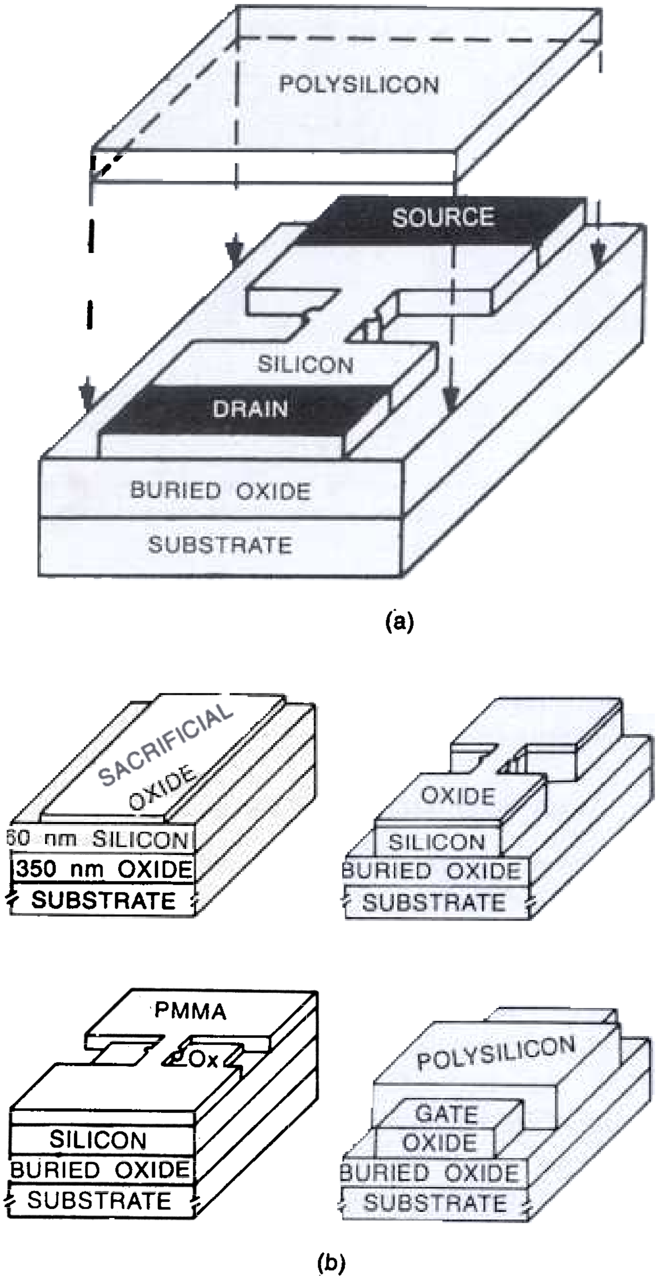

Figure 13. Experimental realisation of resonant tunnel diode using *GaAs* and *AlAs* layers as shown in the inset.

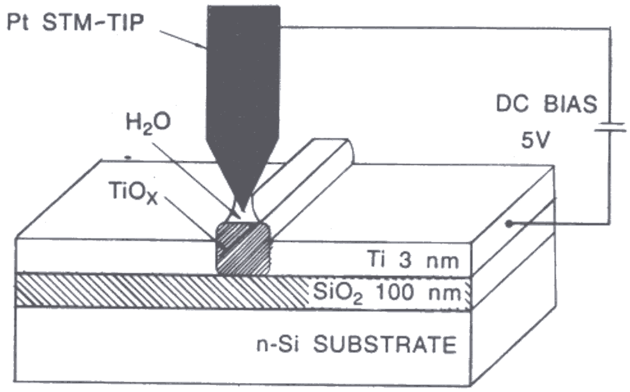

Figure 14(a). Schematics of measuring current-voltage characteristics of *Pt-Al₂O₃-Al* nanostructure using STM.

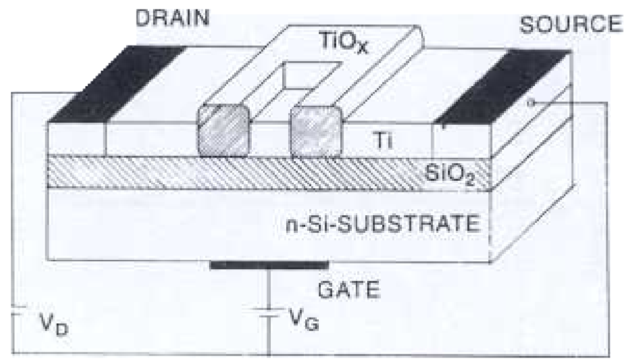

Figure 14(b). Current-voltage characteristics observed single electron transistor made by *Ti* on *p-Si*.

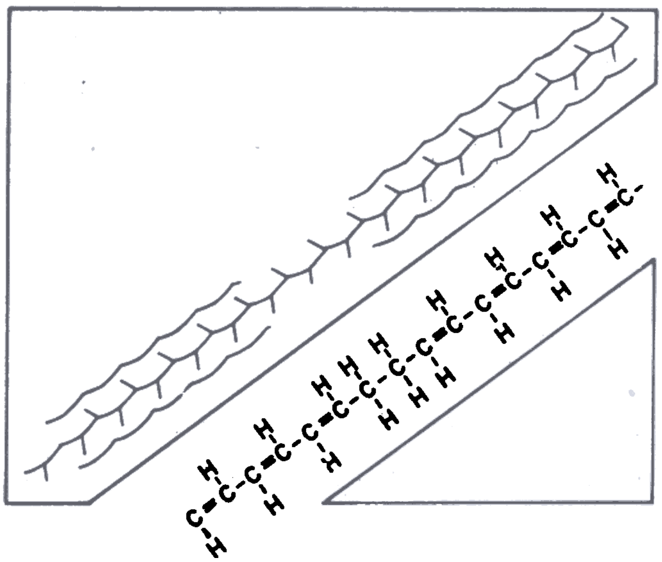

Figure 15. Possibility of realising quantum-dot like situation from two-dimensional electron gas.

individual conducting and insulating molecules. Electrical conduction properties of such molecular arrangements can be studied using μ-STM.

Extending the anology further to individual atoms[25], a chain of few hundred appropriate atoms can be aligned on a suitable insulating substrate. A vacant atom site in the chain may be filled by

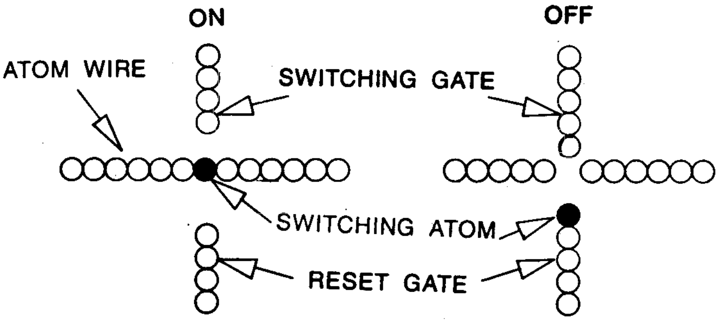

Figure 16. Schematics of a single electron transistor realised out of *Si*.

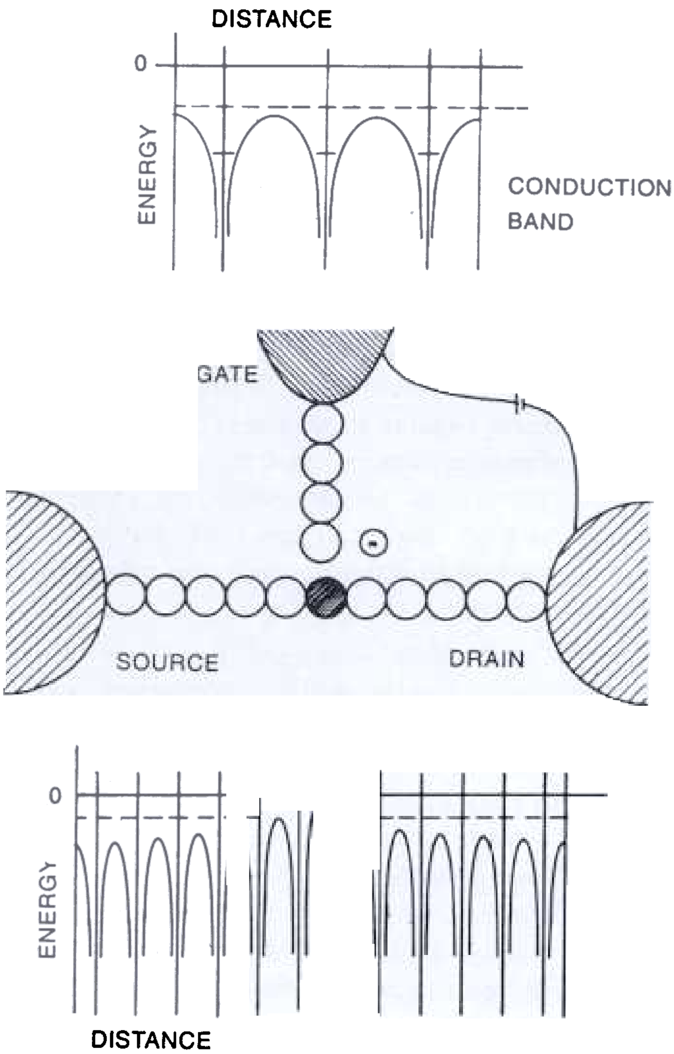

Figure 17. *Ti-TiO$_x$-Ti* single electron transistor structure formations at room temperature using STM.

energising the side chain, such that the path for electron is complete. Single atom, when removed

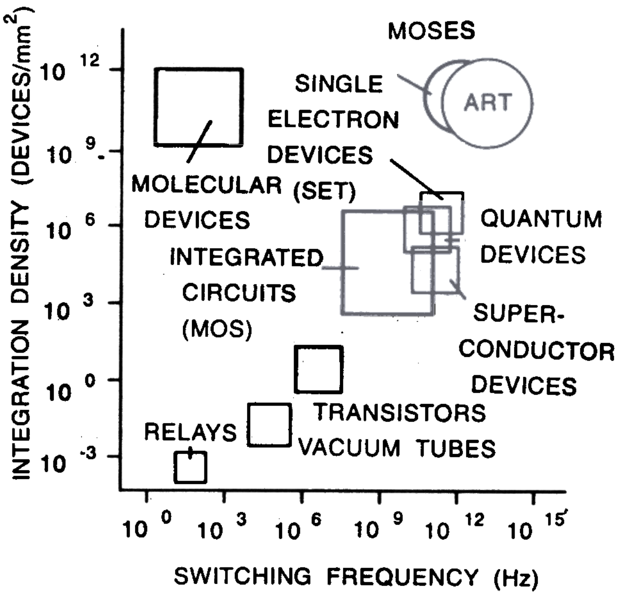

Figure 18. Schematic representation of a switching arrangement using molecules of polyacetylene and polyethylene.

by side chain, would make the switch off. On-off characteristic of such a chain has been simulated using tight binding method for a chain of 200 atoms separated from each other by 0.2 nm. When one electron is injected from one end of the wire by applying 3×10^4 V/cm electric field, electron flows across the wire through resonant tunneling and gets reflected, if chain is broken. Movement of switching atom is controlled by applying a field of 100 mV at the switching and reset gates. Switching speed of such an arrangement will be limited by vibration frequency of atoms involved, which is generally in the range THz. A simulation based on first principle has estimated switching speed of 30 THz. In another configuration[27], an atom chain was made to behave like a field effect device. A small chain of atoms connected at the two ends by conductors can be influenced by the tip of another chain of suitable conductor. A bias applied to the tip of the gate chain would induce field effects and thus cause lowering or raising of the energy levels in the atoms in the chain, which ultimately affects the transport of electrons in the chain. For such field effect structure, only 3-4 atoms are needed. Preliminary estimates for such devices indicate that 10^7 logic gate and 10^9 bit memory would require

20 μm^2 and 200^2 μm, respectively. Longest signal delay will not exceed 10^{-12} s on such a chip of 200 μm^2. Therefore, THz operation is easily possible on such a chip.

A comparison of molecular and atomic switching devices, termed as molecular single electron switching (MOSES) and atom relay transistor (ART), along with other conventional devices, clearly indicate the superior position of such devices for future information electronics applications[25].

Realisation of MOSES and ART devices does not seem to be an impossibility. Continuous efforts being made in the area of materials growth—like atomic layer epitaxy and self-organised growth arising out of highly strained layers, nanolithography involving electron beam, ion-beam and X-ray and nonconventional methods and novel contact fabrication techniques based on superlattice non-alloyed structure, do indicate that such devices can be fabricated in near future. Recent success of fabricating quantum wire and dots with regular behaviour of electronic conduction observed in these structures instills a hope for future success.

6. MATCHING FABRICATION TECHNOLOGY

Quantum effect-based device behaviour predictions can be verified only by fabricating such structures of nano and atomic sizes initially as isolated structures to resolve various issues involved. Next comes the utilisation of this knowledge to realise useful device structures for their exploitation in functional circuit modules. For these, a lithography technique, similar to the one already in use in various forms, has to be developed to handle pattern delineation on the given material with a suitable combination of resist layer pattern forming methodology and finally structure formation. Recent developments taking place in this direction are interesting as there seems to emerge some deviations from the conventional techniques. Figure 22 shows the requirements of submicron, nano and atom technologies along with the resolution of electron, ion and photon-based lithographies[28]. For example, electron-beam lithography can lead to 10 nm feature sizes with suitable modifications. Focussed ion beam (FIB) lithography has also been proven to go to the same limit of 10 nm. Excimer laser and synchrotron radiation (SR)-based experiments indicate limit to few tens of nanometer. Scanning transmission and tunneling microscopic modes are expected to enhance the limit to 1 and 0.1 nm, respectively. A number of resists have been tried out with encouraging results. Well-known PMMA resolves 8 nm features, whereas ZEP and SAL-601 resists could produce 20 nm features in positive and negative modes. Inorganic resists like AlF_3, $NaCl$ and SiO_2 have also been used with scanning tunneling electron microscopy (STEM) arrangement. Carbon patterns have been realised to the size of 8 nm in scanning electron microscopy (SEM). A similar size pattern has been made using PMMA and Ga^+ FIB lithography.

A 50 KV electron beam system[29] using thermal field emitter gun consisting of *Zr/O/W* is reported to produce 10 nm lines with 50 nm period using PMMA resist. Feeding styrene gas ($C_6H_8CH{=}CH_2$) in the above system, *C* patterns ranging from 14-150 nm could be deposited by changing irradiation time. Such *C* films could be used as etching mask in transferring nano size patterns to semiconductors.

FIBs have been developed for lithographic purposes with certain definite advantages over electron beam. Exposure sensitivity of ion beam is two orders of magnitude higher and there is practically negligible ion scattering in the resist and very low backscattering from the substrate. A system[28] using 50 KeV Ga^+ beam having reduced chromatic aberration has been shown to produce 7-8 nm features in 30 nm PMMA on *GaAs* with throughput equal to *state-of-the-art* electron beam setup.

Atomic layer etching involving reactive gas physiosorption, low energy beam-induced reaction and desorption of reaction products, has recently been investigated for defining nano size patterns for device applications[28]. *GaAs* has been etched while feeding Cl_2 gas continuously and applying layer pulses in atomic layer etching mode. Similarly, employing low energy Ar^+ pulses in place of laser, digital etching has been observed[28] in *GaAs*. *Si* atomic layer etching has been observed[28] when F atoms are adsorbed on *Si* surface at low temperature and subsequently 20 eV Ar^+ irradiation is produced. Ar^+ are produced by remote cyclotron resonance plasma (ECR) and F atoms are released by microwave plasma involving CF_4 + 4 % O_2.

STM has been used in various modes to manipulate atoms for patterning purposes. In a STM system, cooled to 4 K, tip is lowered to increase atom-tip interaction and then tip is moved at 0.4 nm/s to the desired location and finally the tip is withdrawn by going into imaging mode. *Xe* atoms and *CO* molecules have been moved to desired location using this technique[28]. Similarly, by applying large electric field to the tip of a field ion microscope, it was possible to evaporate protruding surface atoms as ions. *S* from MoS_2 and *Se* from *WSe* are reported to be evaporated in this manner[28]. *Si* atoms could be extracted from *Si* (111)7×7 surface and relocated[30]. *Au* STM tip has been used as a nanometer size *Au* structures[31]. Here also, the emission process is believed to be of field evaporation type. *W* patterns have been deposited by STM using $W(CO)_6$ organometallic gas. Similarly, WF_6 gas ambient provided *Si* substrate etching using STM[28].

Some novel techniques[28] have been reported recently in connection with nanolithography. Natural lithography, self-assembled lithography, atomic layer lithography and electron holography are some interesting techniques catching attention.

In natural lithography[28], a nondispessive colloid of controllable size is coated on the surface of the semiconductor instead of a resist. An ordered array of 0.8 μm spheres has been produced by spin coating of 15 per cent latex polystyrene $(C_6H_5CHCH_2)_x$ on *Si* substrate at 2400 rpm. Even, protein crystals have been coated and dried followed by shadow deposition of *Ti* at 50° from the normal and a hexagonal array of 10 nm holes with a 20 nm periodicity could be fabricated by ion milling of coated protein surface.

In self-assembled lithograply[28], a monolayer film of organosilane is coated on the semiconductor surface by any one of the methods like dip, spinning or vapour deposition technique, as shown in Fig. 21. This monolayer film is patterned by any one of the sources like deep UV, *ArF* (193 nm), *KrF* (248 nm) lasers, X-ray, electron, ion beams and STM. The latent image in the organosilane film is metallised in electroless deposition using *Pd/Sn* as catalyst followed by metal deposition. Plasma etching produces patterns in the substrate subsequently.

Atomic layer lithography uses a nonatomic layer as resist[28]. In an experiment, a freshly prepared surface of GaAs was oxidised using halogen lamp and O_2 ambient over a period of 1 hr. This thin layer of *GaAs* oxide was patterned by electron-beam in the presence of Cl_2 under pressure. Thus, very fine patterns were delinearted using *GaAs* oxide mask. In another set of experiment[28], a clean *Si* wafer was dipped in $HF{:}H_2O$::1:100, followed by rinse in ultrapure DI water. This atomic *H* termination on *Si* surface was used as resist layer for lithography. In the following step, electron beam exposure removed *H*-termination and formed the required pattern. *Al* is selectively deposited on rest of *H*-terminated area of the substrate after oxidising the *H* desorbed surface due to electron-beam exposure by taking out the wafer to nornal ambient temperature in clean room.

Wavelength of an energetic electron is generally very small. For example, 200 KeV electron possesses 0.087 nm wavelength. For such situations, a hologram can be produced with subangstrom fringe spacings[28]. Using magnified fringe spacings, nanoscale pattern can be generated by electron holography. Some preliminary records of such holograms are encouraging.

7. CONCLUSIONS

Systematic understanding of electron transport in ideal bulk semiconductor followed by modifications in energy-band structure due to superlattice, change in composition in unit cell and strained lattices and ultimately trying one, two and three-dimensional quantisations, indicated towards additional charge carrier features. Early successes in realising quantum charge career sheet, wire and dots, clearly indicate towards the possible extension to molecular and atomic structures for switching applications, involving single electron or hole transitions. The way progress is being made in different areas, it seems quite probable to realise molecular and atomic structures described in this paper. Switching circuits, so realised, will have enormous applications in diverse fields which could not be feasible from today's standard. System design concepts would also need drastic change in methodology in future.

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