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EVOLUTION OF INTEGRATED ELECTRONICS FROM MICROELECTRONICS TO NANOELECTRONICS

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Abstract: Microelectronics is a semi-classical electronics from viewpoints that the behavior of electrons in devices can be treated with the effective mass approximation and the random phase approximation. On the otherhand nanoelectronics is a quantum-mechanical electronics and full use of properties of electron waves, of artificial mini-Brillouin zone, of size dependent energy eigenstates structure and Coulomb blockade of electron tunneling. New circuit implementation techniques are to be explored in nanoelectronics.

1. Semi-Classical Integrated Electronics and Quantum-Mechanical Integrated Electronics

The feature size of integrated semiconductor devices has shrinked form 20μm at the early stage of integrated circuit technology to 0.1 μm or below it at the most modern large scale integrated circuits for the past thirty five years. This shrinkage of semiconductor device size resulted the increase of the number of integrated devices per unit chip area and improved their performance, realizing shorter signal propergation delay time and lower power consumption.

However, the physics involved in device operation has been unchanged during the innovation of device fabrication technology. The physics is based on solid state physics,mainly the energy band theory and the theory of electron and hole transport in semiconductors.

Those theories, of course, are quantum-mechanical, but the effective mass approximation and the random phase approximation for the behavior of electronics and holes have been successfully introduced to understand the performance of devices. In consequence electronics and holes in semiconductor are treated as if they were to be classical particles, and their wave proprieties have become implicit.

The reason that those approximations are valid and useful for understanding the performances of semiconductor devices are the followings. Firstly, the size of the active region of semiconductor devices, such as the base thickness of bipolar transistors and the channel length of MOS field effect transistor(MOSFETs), is much larger than the de Broglie wavelength of electron or hole, so that electron or hole can be treated as a classical particle. Oneexception is the thickness of the channel of MOSFETs and the characteristics as quasi two dimensitioned electron gas have been experimentally observed in the channel of MOSFETs. Secondly, the number of electrons associated with device operation is huge. For example, if a 100fF capacitance is charged by 1V, about 6×10^5 electrons are induced to the electrodes. This illustrates that so many electrons are used as a mass to carry electrical signal and therefore, allows the random phase approximation for electronics transport.

According to the innovation of fabrication technology of miniaturized structures, the physical size of the order of 10nm has been realized. Such small size is not always three dimensional, but two or one diemsnioanl at present stage. Even so new quantum mechanical effects based on the wave nature of electron appear in such small physical systems and a new phase of electronics, called "Quantum Phase Electronics" is now emerging.

Another important feature of nm structures is that their capacitance is so small that the terminal voltage *change* by an elementary charge can be larger than the thermal voltage. This enables us to detect the terminal voltage change of a capacitor by an elementary charge and to use a single electron as signal carrier. This electronics is called Single Electronics, which stands for single electron electronics.

Both Quantum Phase Electronics and Single Electronics have become materialized by making the physical size of structures to nm range, so that naming of "Nanoelectronics", meaning nanometer electronics, can be given to them as a general terminology. In consequence nanoelectronics is truly quantum mechanical electronics, but microelectronics, in which the feature size of devices is conveniently represented by μm as length unit, is semi-classical one. Here it must be emphasized that the above mentioned technical trend does not imply the replacement of microelectronics by nanoelectronics, but advancements of nanostructure fabrication enable the further shrinking of semiconductor devices and the novel applications of quantum-mechanical effects tto he deive operation, resulting a new phase of integrated electronics.

2.Electron Wave Devices

One of the direct applications of the wave nature of electronics is analogous to the applications of electromagnetic waves. Electromagnetic waves are used as carriers to transmit signal through wave guides, which are hollow metal tubes, or coaxial cables. Electron wave transmission lines similar to those are very fine semiconductor wires, whose edge dimension of the cress-section is of the wavelength of electrons. The phase coherence length of electron wave is determined by inelastic scattering of electron, which is phonon scattering in most cases, and therefore dependent on lattice temperature. At room temperature the length is so short as of the order of 10nm, but at cryogenic temperature it reaches to the order of μm. Those are comparable to inter-device distances on future IC chips and on present IC chips, respectively. The advantage of electron wave transmission lines over conventional conducting leads is the reduction of capacitance to the earth and the increase of fan-out of digital gate circuits. Clear demonstration of phase coherency of electron wave is the interference penomena, which has many potential applications. One of them is to obtain negative resistance using interference of electron waves. Phase differnce between two electron waves can be generated by providing two electron wave path with different length(1)or by the Aharonov-Bohm effect associated with electrostatic potential or electromagnetic vector potential(2). Field effect transistors whose operation is based on those principles have been proposed and these operation was experimentally confirmed.

3. Modification of Materials Properties by Quantum Effects

One of the well known quantum-mechanical effects based on the wave nature of electron is the generation of the forbbiden energy band for eigenstates of electrons by periodic potentials in the medium and the reduced zone representation for electronics states in such medium based on the periodic properties of the electron wave function (Bloch function) is useful to describe the eigenstates of electrons.

Commonly periodic potential is introduced into a medium, that is crystal, by constituent atoms, but periodic potential can be introduced in the medium by alternating the composition of the crystal artificially and periodically. A typical example is so called superlattice. One dimensional super lattice, that is, periodically layered structure, has been implemented and used to obtain negative resistance and to filter electron energy by resonant tunneling.

In one dimensional superlattice forbidden bands do not appear in the energy band for conduction electrons, because no artificial periodic potential exists in the plane of each layer and electrons behave like free particles in the plane as far as the effective mass approximation is valid.

However, by introducing two dimensional or three dimensional artificial periodic potentials into two-dimensional electron gas, for instance by building quantum-wire array or quantum dots array into the channel region of a MOSFETs or by selelctive doping to the region or with additional lattice gate structure, forbidden bands are generated in the conduction band. An advantage of introducing forbidden bands into a condition band is to suppress high energy phonon scattering of electrons. The physical mechanism of the suppression of high energy phonon scattering is as follows. If all the carriers are in the ground mini band and if the mini band width Ebm and the mini-forbidden band gap Egm satisfy the following conditions simultaneously,

$$Ebm < \hbar\omega_{min} \text{ .and } Egm > \hbar\omega_{max}$$

where $\hbar\omega_{min}$ and $\hbar\omega_{max}$ are the miniimum and the maximum energy of relevant phonon,t scattering of electros by those phonons cannot take place, because the final state of scattered electrons would be in the mini-forbidden band gap. This will be effective to eliminate the electron velocity situations in silicon at high electric fields[3].

Another quantum mechanical effect, which appears in superlattice structures, is the generation of mini-Brilloiun zone, accompanied with the Brillouin zone folding[4]. The Brillouin zone folding, that is, higher order Brillouin zones can be folded into the first Brillouin zone, is well known as the reduced zone representation. However this well known concept introduces a very interesting and useful phenomena for materials with indirect transition energy band structure. By properly designing mini-Brillouin zones in the first Brillouin zone of medium material, any part in the first Brillouin zone can be folded into the first mini-Brilloin zone. A simple example is that the condition band minima of silicon on <100> axis. Of course the above mentioned just illustrates one dimensional Brillouin zone Folding. In order to obtain efficient light emission, other conduction band minima should be brought to Γ point , too, and three dimensional Brillouin zone folding is required.

Attempts to realize one dimensional Brillouin zone folding with Si-Ge superlattice are being pursued, and if three dimensional Brillouin zone folding succeeds, efficient light emission will be obtained from silicon and opto-electronic integrated circuits and optical inter-connections will be materialized with process compatible with silicon integrated circuits manufacturing.

4. Reduction of Signal Charge to Quantum Limit

Recently low power electronics has become a matter of concern in the field of integrated electronics, because a physical limit of the density of integrated devices per unit area is given by the heat transfer from a chip and the life of batteries is limited. Power dissipation on a chip is composed of bias power dissipation and signal power dissipation.

The former can be suppressed by using CMOS like circuit configuration and the latter can be decreased by making circuit capacitance and voltage small. The reduced voltage operation is severely limited by the operational margin of circuits, affected by the fluctuation of device characteristics such as threshold voltage of MOSFETs and of the patterns of devices and interconnecting lines.

In order to solve this trade-off relation, a physical principle to fix signal charges to a certain small value is required. In Josephson digital circuits, the extreme of small signal magnetic flux is a flux quantum. Similarly the extreme of small signal charge is an elementary charge and quantized digital circuits, which limit the signal charge to an elementary charge, are the future of integrated digital circuits.

A physical principle to limit signal charge to an elementary charge is the Coulomb blockade of tunneling. The terminal voltage of a capacitor charged by an elementary charge must be at lowest ten times the thermal voltage, which is mV at room temperature. This implies that the capacitance must be small as 0.6aF and the electrode area must be small as $(15\text{nm})^2$ if the dielectic between the electrodes has the specific permitivity of 4 and the electrode gap is 10 nm.

Single electron transfer can be realized using the Coulomb blockade of tunneling of electron to a quantum dot and a single electron transistor has been proposed[5]. However, it has been found that the transistors have difficulty to have high gain with high operation speed, so that high speed logic circuits with large fan-out cannot be constructed with single electron transistors.

In order to solve this problem, it is proposed that the digital logic functions are represented by binary decision diagram[6] and the circuits are constructed by making an electron as signal messenger. Such new concepts in circuit configration are needed to single electron circuits practically useful.

5. Quantum Size Effects

Standing electron wave effects based on the effective mass approximation are commonly called quantum size effects. As far as the effective mass approximation is used, the size effect is semi-classical. Real quantum size effects are those which appear when the size of electron system becomes so small that the effective mass approximation is not valid. Atom cluster is an example and conventional energy band scheme does not hold.

Nanocrystals whose size is several nanometer in edge length, shows a quantum size effect, which is size dependent energy eigenstates structure. Electron energy eigenstates are no longer continuous but discrete, and similarly phonon energy eigenstates are also dependent on the nanocrystal size and discrete. In such system efficient radiative recombination of electron and hole may take place even if the energy eignestate structure is similar to the energy band structure of indirect transition[7]. This may show another possibility of efficient light emission from silicon and of silicon optoelectronic integrated circuits.

6. Conclusions

Evolution of integrated electronics from microelectronis to nanoelectronics is made feasible by the innovation of fabrication technology, which is going to reach the stage the so called nanotechnology. In nanoelectronics quantum mechanical properties of electron or electronic system such as those of electron waves, of artificial mini-Brillouin zone, of size dependent energy eigenstates structure and Coulomb blockade of electron tunneling will be fully utilized and new implementation techniques, which can take full advantage of such quantum - mechanical effects in realization of functional circuits should be explored.

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