O-2 (Plenary)

Nano-electronics--A New Field for SISPAD

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1. Introduction to Nanoelectronics

Nanoelectronics is an emerging technology, in which the feature size of devices is of the order of nanometers.

The scaling-down of semiconductor devices composing LSIs has reached to a quarter micron or below it, but no significant change of physics in course of the scaling-down has been involved in the performance of microelectronics devices, such as bipolar transistors and MOSFETs. The reasons are the followings:

(1) The size of the active region, such as the base thickness of a bipolar transistor and the channel length of a MOSFET, is much longer than the lattice constant of the substrate crystal, so that the effective mass approximation for conduction electrons and positive holes (carriers) holds.

(2) The size of the active region is so much longer than the mean free path determined by phonon scatterings of carriers and also so many carriers are involved in one bit signal transfer, that the random phase approximation holds.

However if the size of the active region falls into the nanometer range, the size becomes the same order of the mean free path which is around 40nm in Si at 300K, or even smaller than it. Then carrier transport becomes of course ballistic, and carriers show the wave-like characteristics and the phase coherency as the quantum-mechanical wave is preserved. This phase coherency is a physical basis for electron-wave devices, such as electron waveguides and electron wave interference devices.

The second feature in such miniaturized structure, called nanostructure, is its so small capacitance that the Coulomb blockade of tunneling of carriers can be observed at relatively high temperature as room temperature. For instance the terminal voltage change of 1aF capacitor, which can be realized with the electrode's area of $(10\mathrm{nm})^2$ sandwiching 10nm thick dielectric film whose permittivity is about 10, by one electronic charge change 0.16V, which is much larger than the thermal voltage at 300k. This makes possible observe single electron transfer through a nanostructure and create a new electronics, called single electronics. An advantage of single electronics is low signal power consumption, which is a minimum quantum limit.

Third feature to be noted is the average spacing of dopants, which is around 26nm for the doping level of $10^{17}\ \mathrm{cm}^{-3}$ in Si and this is the third, important physical characteristic length. This indicates that the continuum model for space charge is no longer valid for nanostructures.

2. Taking-Off from Macroscopic SISPAD to Atomic Level One

For determining the electrostatic potential distribution in nanostructures the continuum space charge model is no longer useful as mentiened previously. Similaly transport equations of carriers or dopants with transport coefficients such as mobility and diffusivity do not give results with sufficient accuracy on electrical characteristics of devices and on dopant distribution in substrates.

For transport of carriers Monte Carlo technique has been used to simulate electrical characteristics of small devices. However with Monte Carlo simulation the properties based on the phase coherency of carrier waves cannot be represented. New simulation technique based on the wave-like characteristics of carriers must be explored. This will be not a simple numerical solution of Schrodinger equation with static boundary conditions, because the boundaries themselve are oscillating thermally and scattering carriers.

In continuum models various kinds of characteristic quantity, such as the project range and its standard deviations for the distribution of implanted ions, etching rate and deposition rate, are used, but those are macroscopic quantities and not appropriate for characterizing nanostructure fabrication. Instead of continuum model molecular dynamics should be used.

A possible application of nanoelectrinics phenomenon is single electronics. Single electronics needs novel circuit configuration , because the voltage gain of a single electron transistor is too small to build von Neumann type logic circuits with a large number of fan-out, and tunneling of carriers through a potential barrier is a statistical phenomenon. Those request novel circuit configuration such as binary decision diagram for single electron circuits.

So logic synthesizer and circuit simulator for binary decision diagram with statistical property of tunneling will be more useful in single electronics than in currently existing electronics.

3. Concluding Remarks

Although silicon microelectronics will remain in the main stream of electronics, evolution to nanoelectronics will be emerging. In nanoelectronics the wave-like characteristics of carriers and Coulomb blockade of tunneling of carriers are two principal physical principles and the continuum model for space charge due to ionized dopants is no longer valid.

Atomic level modeling of carrier-wave scattering from the boundary and materials processing, and statistical and dynamical modeling of tunneling of carriers through a potential barrier, and single electron circuits will be a new field of SISPAD for nanoelectronics.

Acknowledgement

The author would like to thank Dr. Shigeo Ihara, Hitachi Central Research Laboratory for the discussions on application of molecular dynamics to semiconductor processing and for the receipt of references related to them.