Neosilicon-Created New Applications

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Introduction

A silicon-based nano-material is one of the new material candidates for the advanced electronics devices. The nano-sized silicon grains connected with tunnel barriers are heterogeneous materials in which carrier trapping, scattering, quantum confinement, tunneling and ballistic transport effects of electrons would apparently play even at room temperature. The new nano-silicon materials with enhanced non-bulk characters should be called as neosilicon.

Recently, wireless mobile networks in local and/or global scale become realistic. From the view point of various mobile applications such as micro-tag, bio-discriminator, mobile phone, net-music player, digital camera and PDA, interest in power consumption of electronic devices such as CPU, memory, display and I/O interface is greatly increasing.

In this report, ballistic-electron-excited light emitting device, nano-electromechanical memory and new functional applications using the neosilicon are intensively discussed, because, the enhanced feature of the electron trapping nature in neosilicon is expected to realize new functional devices for low power consumption demand.

Electron Emitter

Cold electron emission from porous-Si was reported by Sheng et. al. [1]. The most interesting feature of the electron emission is the ballistic-like electron emission with energy peaked at ~10eV as shown in Fig.1.

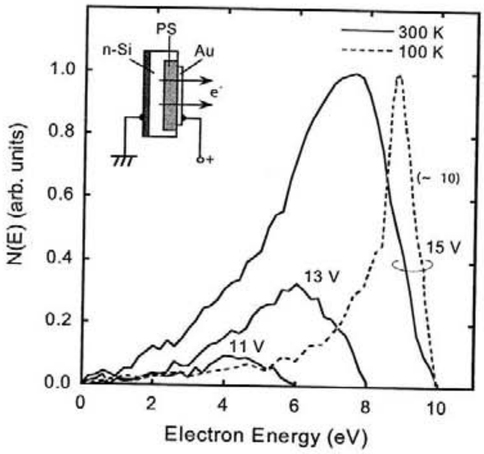

Fig.1 : Energy distribution of emitted electrons and temperature dependence

This feature would realize the light-emitting device by using this electron emitter combined with phosphor as shown in Fig.2.

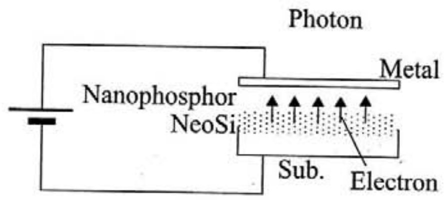

Fig.2 : Ballistic-electron-excited photon emission without vacuum

Emitted electrons from neosilicon injected into the contiguous phosphor create the photons without acceleration space in vacuum. Nano-sized phosphor matches for this purpose. Because, penetration depth of injected electron is roughly the same in size of the nano-sized phosphor of 10nm. In order to realize this device, not only electron emission efficiency of electron emitter is high, but also light emission efficiency of phosphor excited under the very low electron energy of 10-100eV should be increased in contrast to that of conventional phosphor under the electron energy of 1-10keV.

We tried to characterize the nano-phosphor of Y_2O_3:Eu under the low electron energy below 1keV. In the conventional phosphor, quantum efficiency of emission decreases with decreasing the electron energy. In nano-phosphor, quantum efficiency of emission expected to constant down to 10eV range. However, experimental result shows that quantum efficiency of emission gradually decreases with decreasing the electron energy. This tendency is similar to that of the conventional phosphor. More intensive study is needed to realize the above application.

Direction of emitted electrons is roughly confined to that of normal to the emitter surface and energy distribution of emitted electrons is about 4-5 eV at room temperature and 1-2 eV at 100K. As a result, emitted electrons can be confined without focusing lens.

Another interesting feature is that this electron emitter can operate in wide range of environment pressure even at atmospheric pressure because of the emitted electrons having high initial velocity about 10 eV. This feature will open various new applications such as ionization, chemical modification of gases, surface treatment of solid materials, biomedical inspections, disinfection, etc. Original character of this electron emitter is that major emitted electrons have energy of 4-8 eV. This would mean that high-loss acceleration process in the range of 0 to 4eV in certain gas pressure is eliminated. As a result, this electron emitter can operate effectively, and would be useful in chemical reaction application even in the atmospheric pressure.

NENS memory

Another selected device application is non-volatile m emory using nano-electro-mechanical system (NENS) with neosilicon [3, 4]. NEMS have a possibility of high-frequency operation over the GHz regime since the characteristic frequencies are expected to increase with decreasing their dimensions [5].

Figure 3 shows the conceptual structure of this device. Instead of the floating gate in the flash memory, mechanically bistable bent beam having electric charge is situated between main gate and channel of MOS device. The neosilicon would be suitable for electric charge holding in which electrons can be stored in nanosilicon dots affected by single electron charging scheme.

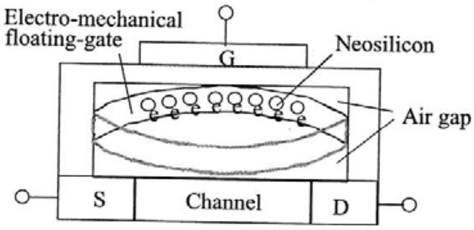

Fig.3 : Nano-electro-mechanical nonvolatile memory using neosilicon

The mechanical bistability gives us the nonvolatility and elimination of high field tunneling process of electrons of this memory. It brings us no-limitation in rewriting number of operations. There are many interesting character and problems such as maximum operation frequency, mechanical dumping process of moving beam, power consumptions at holding, reading and rewriting states, reliability/life, charging method of neosilicon, fabrication method, etc.

From a mechanical analysis of resonance frequency calculation assuming the maximum central displacement of 50 nm, the switching time between two stable states was estimated to be ~ 0.5 ns for a SiO_2 beam with the dimension of $1{,}000\times1{,}000\times100$ nm^3, and ~ 0.05ns for that of 100x100x10 nm^3. This corresponds to the operation frequency of ~ 2 GHz and 20 GHz, respectively. These values are comparable to those of MOS devices. A velocity of moving beam for the former is estimated as 50nm/0.5ns=100m/s which is less than sound velocity in the air. In the latter, the velocity is estimated as 1,000m/s. However, in the latter, the displacement of 50nm is a half of the beam length of 100nm which is not realistic. In this case, the displacement of 10nm will assumed which leads to the velocity of 200m/s.

Operation mode, that is, transfer mode of the beam between convex and concave strongly affects to transfer speed and transfer energy. Figure 4 shows various transfer modes of the beam. Direct transfer mode between convex and concave passing through the flat state of the beam has the highest speed and energy dissipation of the action. The energy dissipation of the action is essentially decided by stretching mode of the beam. In contrast to this stretching mode transfer, transfer passing through 1st order bending mode needs the lowest energy dissipation and transfer speed. Higher order transfer mode expected to be in middle.

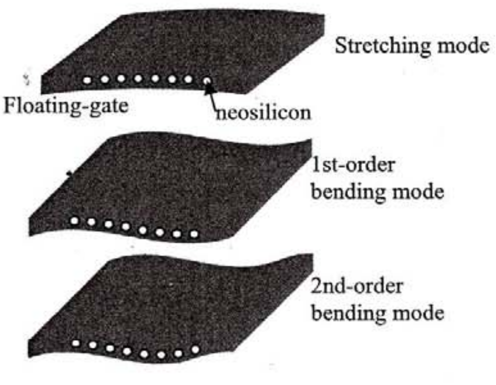

Fig.4 : Operation modes of NENS beam

By optimizing the beam structure, operation mode and stored charge amount, we may build an extremely fast and non-volatile memory.

To characterize the basic nature of the beam experimentally, a single layer SiO_2 beam structure was fabricated using a dry etching Si undercut technique as shown in Fig. 5(a). The most of the fabricated samples showed convex-shaped beams as shown in Fig. 5(b), and this is considered as a result of release of mechanical stress stored in SiO_2 after removing a Si layer underneath. By applying the mechanical force using thin tip loader, the beam shape changes into concave shape which maintains the shape after removing the load. The bistable states can be realized and switched by applying an external force.

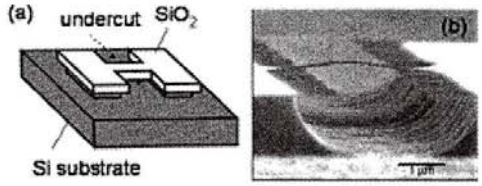

Fig 5 : (a) A schematic illustration of a single layer SiO2 beam structure; (b) SEM image of a convex-shaped beam after etching a Si layer underneath.

In this experiment, SiO2 is used for beam. However, neosilicon beam should be realized [6].

Next, importance of the dumping of the motion of the beam shuld be pointed out. In case of Flash memory, electron injected into the floating memory gate rapidly loses momentum energy, that is "well dumped". In contrast to the situation of the electron, dumping process of movement of NEMS not clear.

Possible dumping processes as follows:

- Internal friction loss of mechanics.
- Friction loss of surface/interface/surface modifier of mechanics.
- Electrostatic interaction loss of internal current flow.
- Electrostatic interaction loss with environment of NEMS (mirror current loss, etc.).
- Viscosity loss of environment of NEMS (air/gas/liquid,etc.).

More intensive discussion on each dumping process in nano-sized region is needed.

Basic discussion points on the non-volatile NEMS memory for industrial use and comments on the present stage is as follows:
(1) Operation frequency can be realized over GHz? - - Yes, over 10GHz can be realized.
(2) Velocity of movement of nano-parts is reasonable in case of 10GHz operation? - - Yes, it is roughly the same as sound velocity in the air.
(3) Because motion of the mechanics is vector in contrast to scalar value of electric charge, various modes of motion exist. Is it bending, stretching or twisting? - - Yes, it should be selected and used for memory. In the case of bridged beam, 1st order bending mode operation seems to be suitable.
(4) For binary operation of the NEMS memory, is dumping of mechanical motion clarified? Friction in the material, air dumping? - - Yes, there are various dumping scheme, but it is big problem should be discussed.
There are various other problems, that is, power consumption, integration density, I/O interface between device and outside, reliability, fabrication process and charging method of the beam in the device. Especially, fabrication process in interacting environment between chemical reaction and mechanical motion in nanospace is interesting new research field.

Summary
Ballistic-electron-excited light emitting device and non-volatile NEMS memory using neosilicon were discussed.

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