NeoSilicon: A Novel Functional Material for Future Electronics

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We propose NeoSilicon in which both particle size and interparticle distance of nanocrystalline silicon (nc-Si) quantum dots are precisely controlled. New functions in electron transport, photon emission and electron emission are expected due to quantum effect at room temperature and large interaction between dots. The bandgap of NeoSilicon is determined by the size of nc-Si dots. The electrical conductivity is controlled by tunneling barrier height and distance. The carrier transport is also influenced by the charging effect due to the small capacitance of each dot.

Possible applications of NeoSilicon include key devices in the field of ULSI, displays and solar cells. Ultralow-leakage current transistors, based on enhanced bandgap of NeoSilicon, can be applied to very high performance memory devices with low power consumption, ultrahigh density, high-speed operation and long retention time. High efficiency light emission and electron emission can be useful in display devices. Combination of these features leads system-on-chip and system-on-panel. Quantum cellular automata can be implemented by ultimately controlled NeoSilicon.

The research plan includes preparation of NeoSIlicon, characterization of electrical and optical properties of nanoscale silicon, light/electron emission from NeoSilicon and its application to electronics industry. Therefore the project team consist of experts of crystal growth, plasma physics,

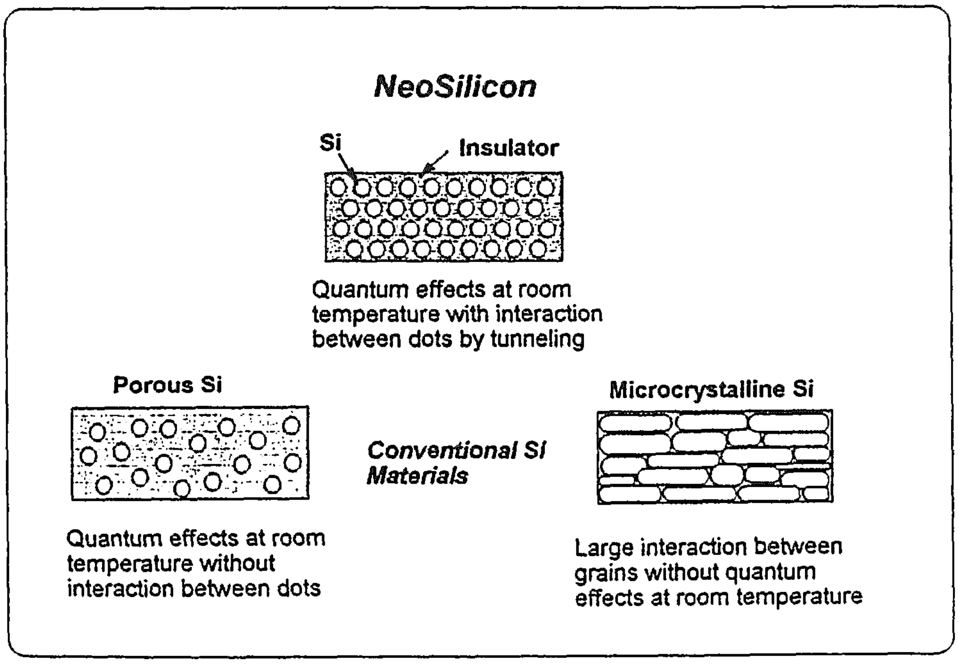


Figure 1: Concept of NeoSilicon

Table 1: Team "NeoSilicon"

S. Oda	Tokyo Inst. of Tech.	(Preparation of NeoSilicon, Electrical and optical characterization)
N. Koshida	Tokyo Univ. of Agri. and Tech.	(Electron emission, Photon emission)
H. Ahmed	Cambridge University	(Transport in nanoscale Si devices)
K. Nakazato	Hitachi Europe Ltd.	(Single electron devices and circuits)
T. Shimada	Hitachi Ltd.	(Electronics applications and systems)

radical chemistry, nanostructure processing, electron transport in low-dimensional structures, luminescence from nanoscale silicon, electron emission, single electron devices and circuits, and semiconductor device industry as shown in Table 1.

The technical challenges include monodispersed quantum dot size of 3-4nm, uniform interparticle distance of 1-2nm, and periodic position control.

We have developed a unique method for the fabrication of nc-Si particles with size less than 10nm by the very high frequency plasma enhanced decomposition of silane. (Figure 2) Size control is accomplished by separating the nucleation and the crystal growth process with a hydrogen gas pulse sequence. (Figure 3) We have also found that argon dilution markedly enhances the deposition rate of nc-Si due to the more efficient plasma activation by heavier argon ions. Transmission electron microscopy observation has clarified that these nc-Si

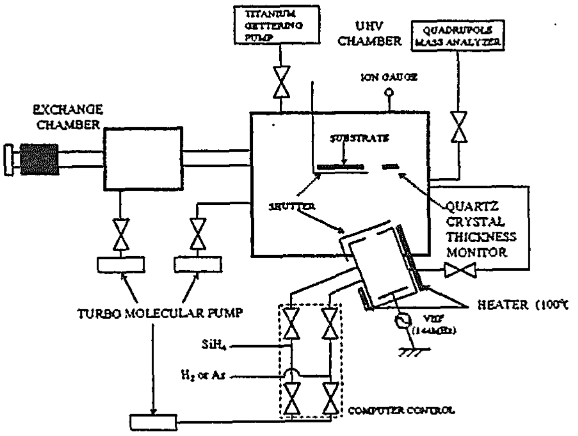


Fig. 2: nc-Si fabrication apparatus

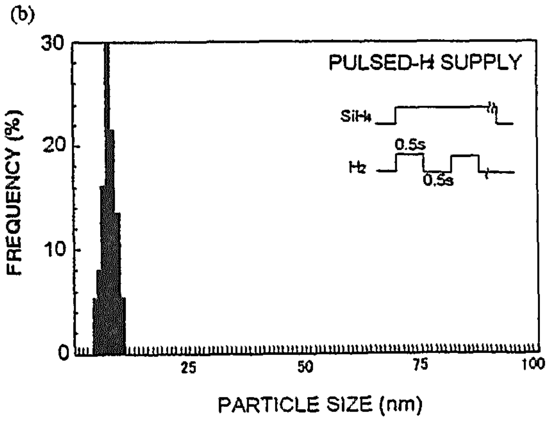


Fig. 3: Particle size distribution of nc-Si

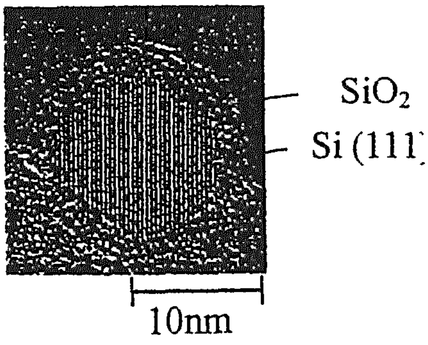


Fig. 4: HRTEM image of nc-Si

particles are twin-free single crystals. (Figure 4)

For the further size reduction, we have reinforced the pumping system of nc-Si fabrication apparatus, which allows the modification and optimization of pulsed plasma processes, such as shorter duration periods of gas pulse and higher pumping rate. In addition, oxidation and etching of nc-Si may be helpful. Self-limiting oxidation in Si nanostructure due to stress in the nanoscale oxide is promising for the preparation of ultimately monodispersed system. We have found experimentally the retardation of oxidation rate by TEM observation (Figure 5) and with increasing oxidation time photoluminescence peak shows blue shift at first due to shrinkage of nc-Si size followed by red-shift due to induced stress at the interface between nc-Si and oxide. (Figure 6)

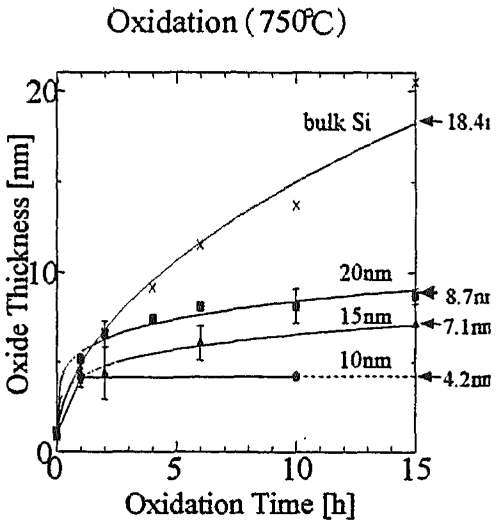


Fig. 5: Oxide thickness vs time

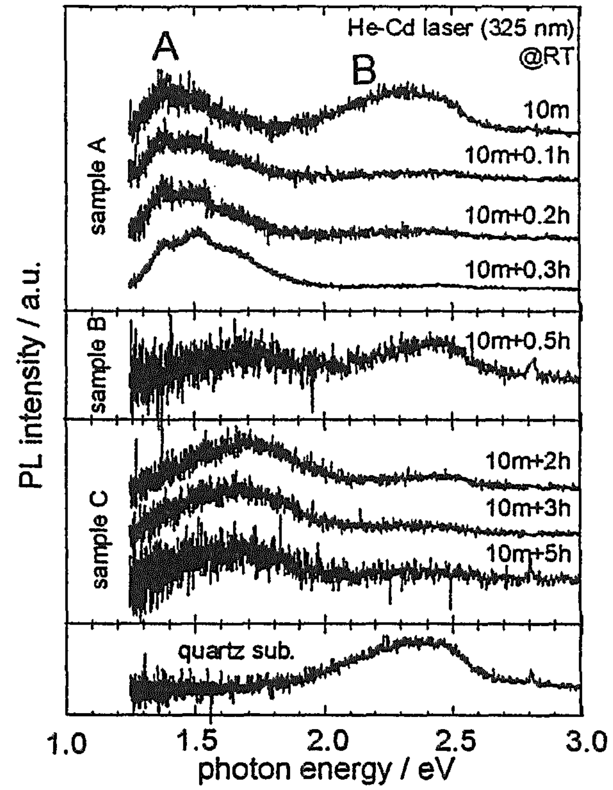
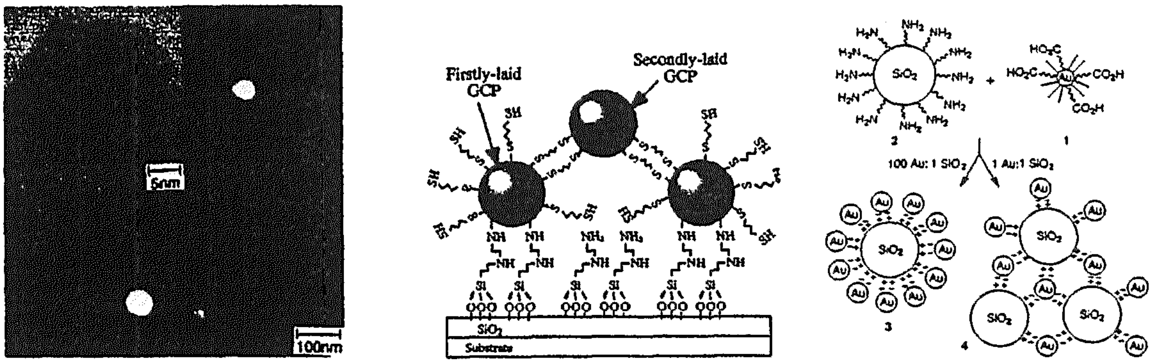


Fig. 6: PL spectra of nc-Si with oxidation periods

Surface oxide plays very important roles in NeoSilicon; besides controlling the dot size, passivation of surface dangling bonds which control transport and optical emission properties, a tunneling barrier which controls transport processes, and fixing nc-Si particles onto the substrate. Direct nitridation of nc-Si is a promising alternative method. Lower barrier height compared to oxide provides higher transmittance. Very thin direct nitride films contain lower trap density compared to SiO_2. Very uniform thin films can be prepared using self-limiting growth mechanism. Chemical selectivity provides more flexibility in processing. Stability of devices will be improved due to passivation effect.

Position control of Si dots is a big challenge. We could manipulate the position of nc-Si using AFM tip, since as-deposited nc-Si dots did not stick to the substrate firmly. We also found that nc-Si dots preferentially locate at the atomic-layer steps on the substrate. Chemical modification of the substrate and the surface of nc-Si is an interesting approach. Ionized nc-Si particles can also be trapped electrically by the strong electric field applied between nanoscale gap electrodes.



Otobe, Oda et al. (1998)

Sato, Ahmed et al. (1997)

Galow et al. (2000)

Fig. 7: Some approaches for position control of nano particles.