Development of Photodetectors using Si Quantum Dots

Mitsuhisa Ikeda[1], Masayuki Kitaura[1], Seiichi Miyazaki[2] and Shin Yokoyama[1]
[1]Research Center for Nanodevices and Systems
Hiroshima University, Kagamiyama 1-4-2,Higashi-Hiroshima
[2]*Department of Electrical Engineering, Graduate School of Advanced Sciences of Matter*
Hiroshima University, Kagamiyama 1-3-1,Higashi-Hiroshima

1. Abstract

Si rich silicon oxide films (SiO_x, x<2) deposited by plasma enhanced chemical vapor deposition at different gas flow rate ratio ($[N_2O]/[SiH_4]$) was annealed at high temperature to form Si nanocrystals (quantum dots) embedded in SiO_2. Raman and photoluminescence spectra confirm the formation of Si nanocrystals for the films with $[N_2O]/[SiH_4]=5$. The current – voltage characteristics were also presented.

1. Introduction

Nanometer-size silicon structures have been extensively studied because the possibility as a light emitting material. It is reported that silicon quantum dot exhibits a significant blue shift of the optical absorption edge and the efficient light emission occurs at room temperature [1]. The Si quantum dots are also expected to be a photoconductive material. In the quantum dot photodetector, the spectral response characteristics are controlled by the size of the quantum dot because of the quantum confinement effect. When a semiballistic carrier transport in the Si quantum dots/SiO_2 system occurs, the impact ionization rate is expected to be higher than that of the single crystal Si [2]. So far, photoconductivity is reported in the Si quantum dot/SiO_2 multilayers prepared by repeating a sequence of low-pressure chemical vapor deposition for dot formation and thermal oxidation for dot isolation [3]. To obtain high photosensitivity for stacked layer structures of Si quantum dots/SiO_2, controlling the dot density and the oxide thickness are of great importance, because the electron tunneling between neighboring Si quantum dots limits the transport of the photoexcited carriers.

In this paper, to develop a photodetector based on Si quantum dots, we have formed Si nanocryatals embedded in SiO_2 by high temperature annealing of Si rich oxide and characterized their properties.

2. Sample Fabrication

The Si rich silicon oxide films were deposited on n-Si(100) substrates with a resistivity of 0.01 Ωcm by plasma-enhanced chemical-vapor deposition (PECVD) with a mixture of 10% silane diluted with H_2 and N_2O gases. A capacitively-coupled PECVD reactor was connected with a 13.56 MHz generators through a matching circuit. To control the amount of excess Si atoms in the Si rich oxide, gas flow rate ratio ($[N_2O]/[SiH_4]$) was changed from 0.5 to 5. The substrate temperature, gas pressure and RF power were 300 °C, 1 Torr and 100 W, respectively. To agglomerate excess Si atoms, the samples were annealed in N_2 ambient at temperature of 1000°C for 30 min. For the measurements of electrical characteristics, semitransparent Au electrode with a typical diameter of 1mm was deposited by thermal evaporation (Fig. 1).

3. Results and Discussion

For characterization of the structure of the films thus prepared, Raman scattering spectra were measured under a right-angle scattering geometry, in which a 530nm light from a semiconductor laser was incident to the sample surface in an Ar atmosphere at a glancing angle of approximately 10°. Figure 2 shows Raman spectra for annealed Si rich oxide for $[N_2O]/[SiH_4]=0.5$, 3, 5. For the case of $[N_2O]/[SiH_4]=0.5$ and 3, Raman spectra show sharp peak at around 520 cm^{-1}, which is characteristic of the TO phonon mode in the crystalline phase. This result means the decomposition of Si rich oxide into a two phase state consisting of crystalline Si and SiO_2 by high temperature annealing [4]. For the case of $[N_2O]/[SiH_4]=5$, the Raman spectrum shifts towards lower frequency and becomes broader compared with the case of $[N_2O]/[SiH_4]=0.5$ and 3. This result indicates the formation of nanocrystalline Si. In nanocrystals, the phonons are localized in small crystallites, and momentum is no longer well defined according to the uncertainty principle, allowing phonons without zone center to contribute to the Raman spectra. Therefore, shift of the peak

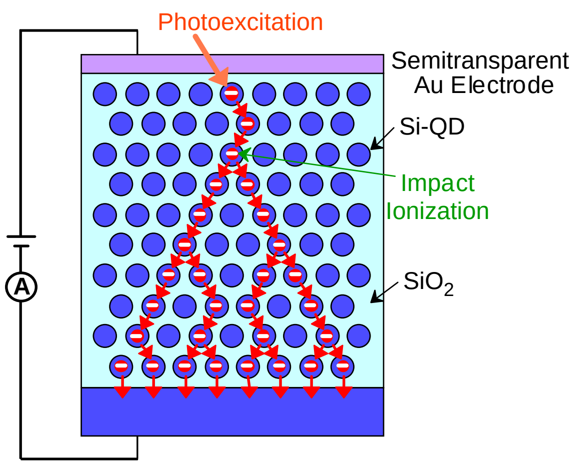


Fig. 1 Schematic illustration of a photodetector using Si quantum dots.

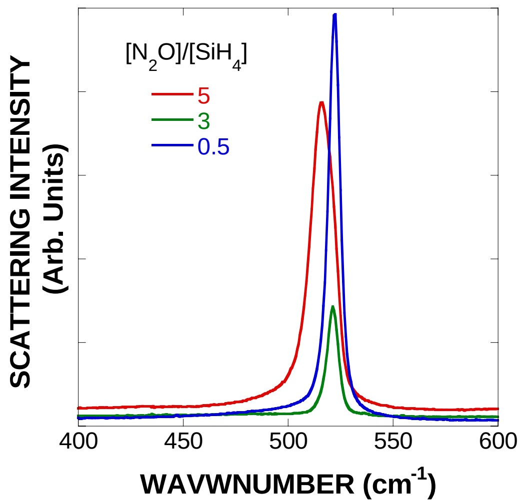


Fig. 2 Raman spectra for Si rich oxide annealed at 1000°C for 30min.

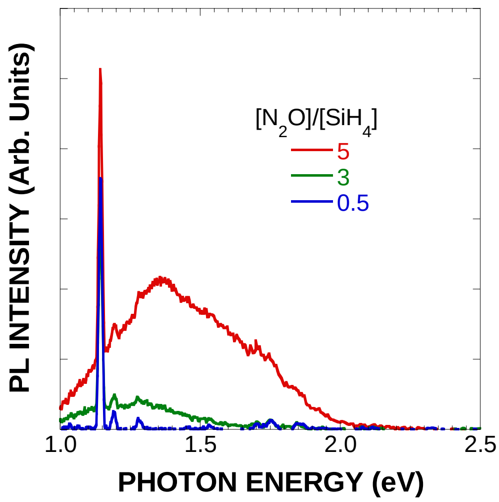


Fig. 3 PL spectra for Si rich oxide annealed at 1000°C for 30min.

position and broadening of the Raman spectrum is observed. The size distribution of the Si nanocrystals also results in broadening of the Raman spectrum.

The photoluminescence (PL) from the annealed Si rich oxide are measured at room temperature using a 325 nm (3.81 eV) light from a He-Cd laser as shown in Fig. 3. For the case of $[N_2O]/[SiH_4]=3$ and 5, the samples show broad PL with a peak at 1.4V in addition to the PL from the Si substrate at 1.1V. The strong eye–visible PL was observed for the case of $[N_2O]/[SiH_4]=5$. The obtained PL is likely to be the same as in the case of luminescence from porous silicon or Si quantum dots which surfaces were thermally oxidized [1]. In these cases, it is suggested that the absorption process is mainly governed by the Si quantum dot and the PL from the Si quantum dots is caused by radiative recombination through localized states existing at the interfacial Si layer between the Si quantum dot and the SiO_2 surface layer. The broad PL is explained on the basis of the inhomogeneities of the sample such as the size distribution or the energy distribution of luminescent centers.

Figure 4 shows current versus voltage (I-V) characteristics of the annealed Si rich oxide measured at room temperature. The current increases with decreasing the gas flow ratio $[N_2O]/[SiH_4]$. An increase in conductivity is attributed to increasing excess silicon content in the films. The behavior of I-V characteristics for $[N_2O]/[SiH_4]=0.5$ and 3 is different from that for $[N_2O]/[SiH_4]=5$. This result implies the formation of Si nanocrystals well separated by SiO_2 for $[N_2O]/[SiH_4]=5$.

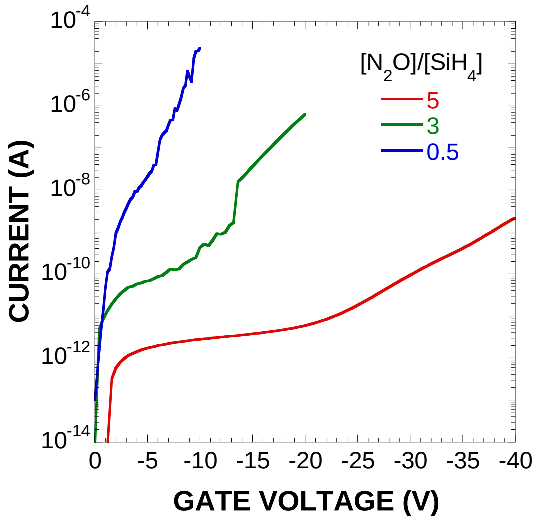


Fig. 4 I-V characteristics for Si rich oxide annealed at 1000°C for 30min.

4. Summary

Si nanocrystals embedded in SiO_2 was formed by annealing Si rich oxide films at 1000 °C. The composition of Si rich oxide films were controlled by the gas flow rate ratio $[N_2O]/[SiH_4]$ in PECVD. Raman and PL spectra indicate the formation of Si nanocrystals for the films with $[N_2O]/[SiH_4]=5$. The strong eye-visible photoluminescence was observed. The I-V characteristics of Si nanocrystals embedded in SiO_2 were also presented.

Acknowledgement

This work was partly supported by the "Nanotechnology Support Project" and "Special Financial Support of Education and Research" of the Ministry of Education, Culture, Sports, Science and Technology (MEXT).

References

[1] K. Shiba, K. Nakagawa, M. Ikeda, A. Kohno, S. Miyazaki and M. Hirose, "Optical Absorption and Photoluminescence of Self-assembled Silicon Quntum Dots ", Jpn. J. Appl. Phys., Part 2 **36**, pp. L1279-1282, 1997.

[2] N. Koshida, X. Sheng and T. Komoda, "Quasiballistic electron emission from porous silicon diodes", Appl. Surf. Sci. 146, pp. 371-376, 1998.

[3] Y. Hirano, F. Sato, S. Aihara and N. Saito S. Miyazaki and M. Hirose, "Photoconductive properties of nanometer-sized Si dot multilayers", Appl. Phys. Lett., 79, pp. 2255-2257, 1998.

[4] P. Mishra, K.P. Jain, "Raman, photoluminescence and optical absorption studies on nanocrystalline silicon", Materials Science and Engineering B95 , pp. 202 – 213, 2002.

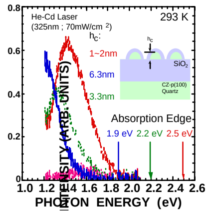
Development of Photodetectors Using Si Quantum Dots

Mitsuhisa Ikeda[1], Masayuki Kitaura[1], Seiichi Miyazaki[2] and Shin Yokoyama[1]
[1]Research Center for Nanodevices and Systems, *Hiroshima University*
[2]*Graduate School of Advanced Sciences of Matter, Hiroshima University*

Background

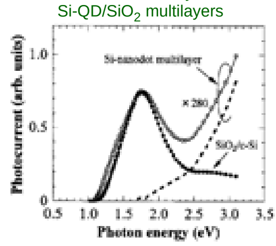
Appliction of nanometer-size silicon structures to optoelectronic devices

Photoluminescence from Si quantum dos



K. Shiba et al., JJAP 36 (1997) L1279.

Photoconductivity in $Si-QD/SiO_2$ multilayers

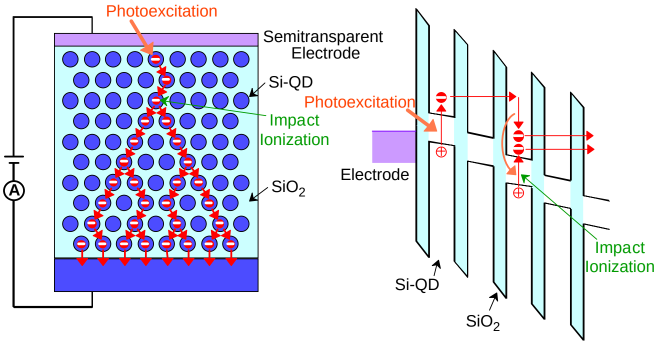


Y. Hirano et al., APL 79 (1998) 2255.

This Work

Fabrication of Si Quantum dots embedded in SiO_2 by high temperature annealing of Si rich oxide and characterized their propertiesto to develop photodetectors based on Si quantum dots

Stacked Si Quantum Dots Photodetector

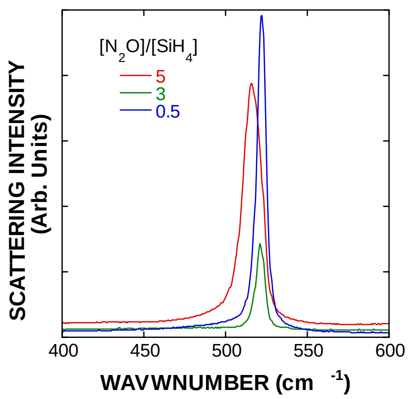


Sample Fabrication

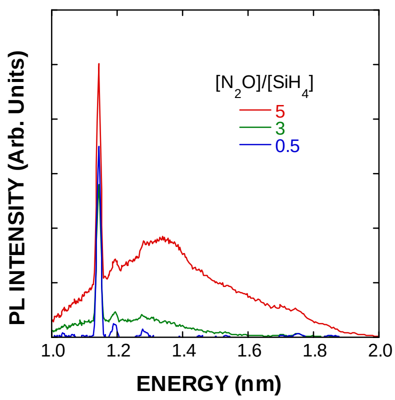
n^+Si(100), 0.01ž cm

- Deposition of Si rich oxide (PECVD)
  - 10%SiH_4 diluted with H_2 + N_2O, 1Torr
  - $[N_2O]/[SiH_4]$=0.5-5
  - Substrate temperature: 300°C
- Anneal
  - 1000°C in N_2, 30min
- Au evaporation
  - Semitransparent Au electrode
  - Diameter: 1mm

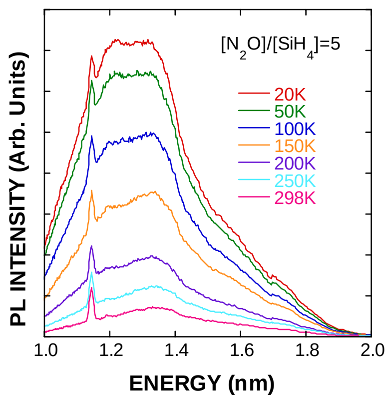
Raman Spectra for Si Rich Oxide after Annealed



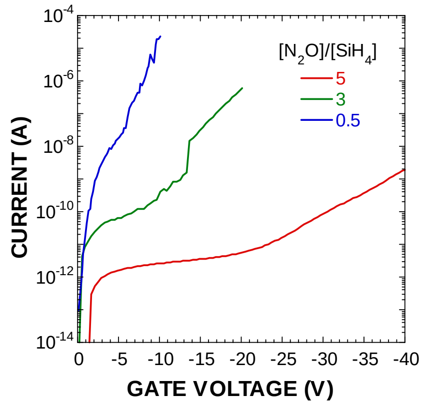
PL Spectra for Si Rich Oxide after Annealed



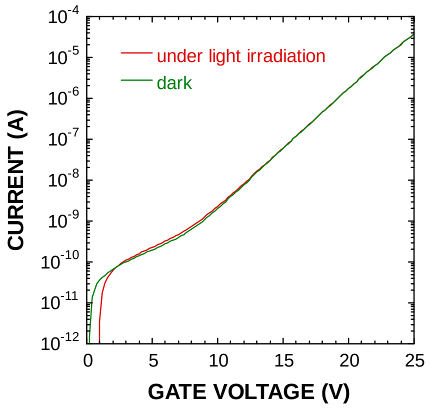
Temperature Dependence of PL Spectra



I-V Characteristics for Si Rich Oxide after Annealed



I-V Characteristics under Light Irradiation



Summary

Si nanocrystals embedded in SiO_2 was formed by annealing Si rich oxide films at 1000°C.
The composition of Si rich oxide films were controlled by the gas flow rate ratio [N_2O]/[SiH_4] in PECVD.
Raman and PL spectra indicate the formation of Si nanocrystals for the films with [N_2O]/[SiH_4]=5.
The strong eye-visible photoluminescence was observed.
The I-V characteristics of Si nanocrystals embedded in SiO_2 were also presented.