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# Functions and Device Applications of Quantum-sized Silicon

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## 1. Introduction

The present device technology is based on the excellent material properties of silicon and advanced nanofabrication processing. The scaling law in ULSI should remain basically effective even if the design rule reaches several nanometers, since the exciton Bohr radius in silicon that is a measure of the quantum size is extremely small (4.7 nm). Below this size, the silicon device concept necessarily gets into the quantum zone from the conventional scaling one.

The carrier confinement effect makes the material feature of silicon totally different from the original one of bulk single-crystalline silicon (c-Si). As a typical example, the band gap of nanocrystalline silicon (nc-Si) is significantly widened dependent on its diameter. As a result, nc-Si exhibits efficient visible luminescence and related photonic effects. In addition to the optical activity, the characters as a confined material appear in the electrical, thermal, and surface properties of nc-Si [1]. The present status of studies on these feature of silicon are described here including the development of novel devices.

## 2. Functionality of nc-Si

Quantum-sized silicon can be obtained from either wet or dry processing. The quantum properties as nc-Si are typically observed in anodized porous silicon consisting of a great number of nc-Si dots packed with a very high spatial density. The major features induced in nc-Si are listed in **Table 1**, including their origins and possible applications. Optically nc-Si behaves as a wide-gap luminescent semiconductor with a relatively low refractive index. These are attractive for the use as photonic components such as electroluminescence (EL) diodes [2], waveguides, optical microcavity, and nonlinear optical device.

The specific effect appears also in the electrical property. Observed strong carrier charging and specific ballistic electron transport effects are applicable to a light-emissive non-volatile memory and surface-emitting cold cathode, respectively. On the other hand, complete carrier depletion in nc-Si drastically reduces the thermal conductivity. A big contrast in the thermal properties produced between nc-Si and c-Si makes it possible to generate ultrasound emission by thermal excitation without mechanical surface vibrations [3]. Further remarkable property of nc-Si is a high surface chemical activity compatible with biological applications [4] to drug delivery, scaffold for bio-sensing, and medical diagnosis. All these effects, characteristic of nc-Si, would open the new frontier different from the conventional silicon technology.

## 3. Topics on Device-oriented Issues

To make the foundation of nc-Si photonics more solid, it is important to determine the limiting luminescence quantum efficiency and to find the way for getting it. Based on the assumption that the complete surface termination of nc-Si dots to suppress non-radiative carrier recombination is key factor for the efficient luminescence, we employed high-pressure water vapor annealing (HWA) at 2-3 MPa and 260 °C for a few hours to anodized nc-Si samples. The photoluminescence (PL) intensity has been significantly enhanced by HWA without shifts of the emission band as shown in **Fig. 1**. After HWA treatment under the appropriate conditions, the external quantum efficiency of the red PL of PS has been increased up to 23% [5]. In accordance with analyses of electronic structure, nc-Si surfaces are passivated well by high-quality oxides with a sufficiently low interfacial defect density. This technique is promising as a low-temperature processing to enhance and stabilize the EL emission.

Regarding the ballistic electron emission from nc-Si diodes, its usefulness has been demonstrated by the applications to a 7.6-inch full-color flat panel display [6], the operation in atmospheric pressure ambience as a negative ion source [7], and the fabrication of a solid-state ballistic lighting device (**Fig. 2**) [8]. Recent experimental [9] and theoretical [10] analyses verify that there is a specific ballistic transport mode in nc-Si dot chains interconnected via tunnel oxide films. The HWA treatment enhances the ballistic emission stability as well.

In contrast to the conventional piezoelectric transducers, the thermally-induced nc-Si ultrasound emitter exhibits a completely flat frequency response in the ultrasonic range as shown in **Fig. 3**. So an ideal acoustic output pulse with no reverberations can be generated under an impulse drive as shown in **Fig. 4**. This is directly applicable to a probe for image sensing of three-dimensional objects in air [11]. In addition, the acoustic signal can be generated in arbitrary frequency and time domains. Actually, the availability of this device for bio-acoustic research has been confirmed by the experimental work for reproduction of mouse-pup ultrasonic vocalizations [12].

### 4. Summary

Quantum-sized nc-Si is a useful functional material with novel technological values in optoelectronic, acoustic, and biophysics applications. By combining these complementary properties with advanced ULSI technology, the importance of silicon devices will be further amplified toward functional integration.

## References

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**Table 1.** Effects induced in nc-Si and their technological potential.

| Effects | Phenomena | Functions | Applications |
|---|---|---|---|
| Confinement | Band gap widening | Visible luminescence | EL device, Optical gain |
| | Low refractive index | Low-$\kappa$, Nonlinear optics | Isolation, Waveguide & Cavity |
| Field effect | Carrier charging | Electrical hysteresis | Loght-Emissive Memory |
| | Multiple-tunneling | Ballistic transport and emission | Flat panel display, Ion source |
| Carrier depletion | Thermal insulating | Ultrasonic generation | 3-D Sensor, Super tweeter |
| Surface effect | Chemical activity | Bio-compatibility | Scafold for sensing, Medical |

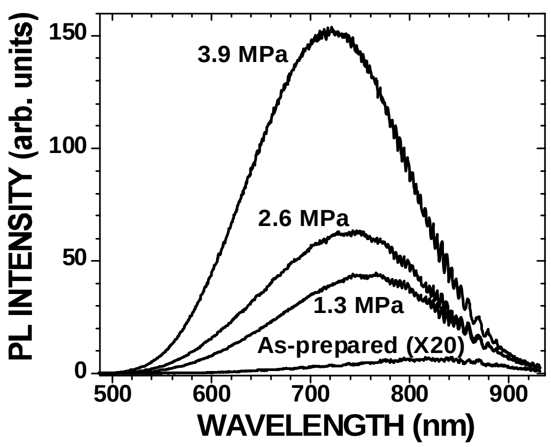


**Fig. 1**. HWA effect on PL spectra of anodized nc-Si formed on p-type Si. The PL is drastically enhanced with increasing the HWA pressure.

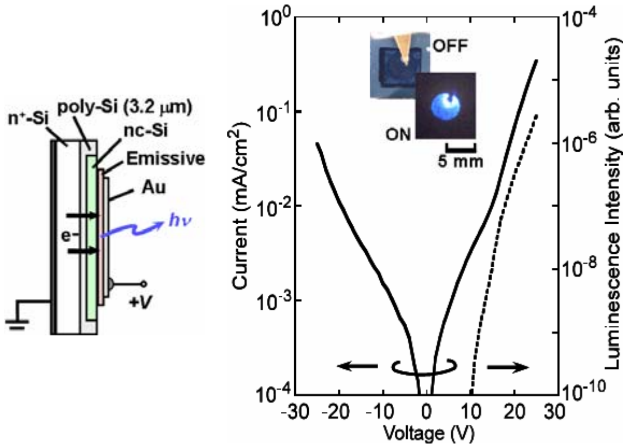


**Fig. 2**. Structure of solid-state ballistic lighting device and the emission characteristics. In the forward bias region, a uniform emission is observed

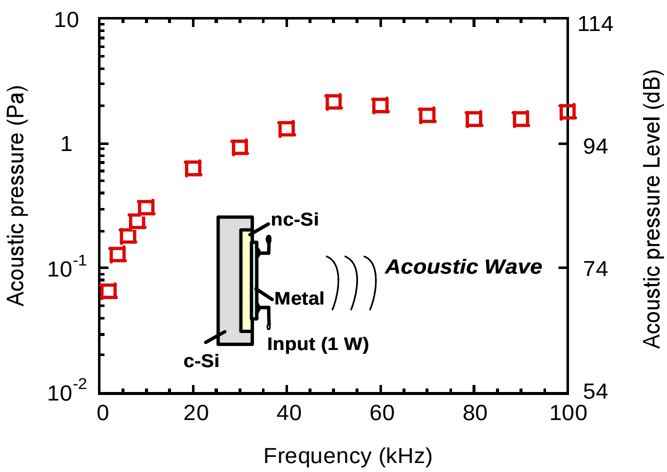


**Fig. 3**. The device configuration of a thermally induced nc-Si ultrasound emitter and the measured frequency response.

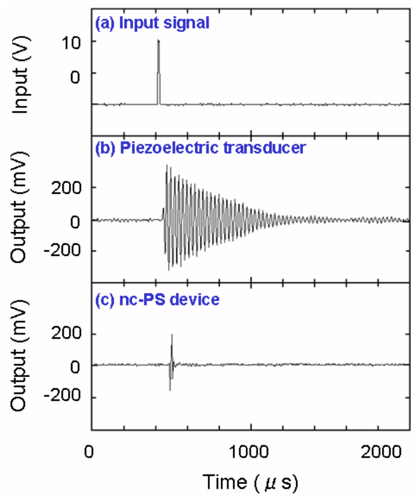


**Fig. 4**. Impulse drive (a) and the corresponding output acoustic signal of piezoelectric (b) and nc-Si (c) devices (in collaboration with MEW Co.).