# **Prospects of Nanostructure Devices for Ubiquitous Information Network**

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## 1. Introduction

With dramatically increased information traffic and extended demand for seamless communications, development of broadband and wireless network is indispensable for realizing ubiquitous information society, in which people can communicate with anybody/anything at anytime and anywhere. In such information society, high-performance advanced devices play key roles, including ultra-low power SOC, photonic devices, wireless devices and thin-film sheet display devices. These technologies will be based on nano-scale structures and device technologies.

In this paper, we address prospects of nano-scale structures and device technologies for future IT network devices toward the ubiquitous information society with emphasis on quantum dot devices. We show how the unique features of the nanostrcurures create innovations in the device technologies. The discussion includes nanostructure growth and devices physics for applications to quantum dot photonic devices. Furthermore, progress in the control of quantum states is also addressed for future quantum computation devices.

## 2. Progress in self-assembled quantum dots

Since the first proposal of the quantum boxes (quantum dots) in 1982 by Arakawa and Sakaki to confine electrons and holes three-dimensionally[1], various efforts have been devoted to realizing the quantum dots for bringing up nanodevices to the real world. The nanodevices include laser diodes, detectors, single photon emitters and single electron memory devices.

Figure 1 (a) and (b) show a copy of the paper published in 1982 and a statistic of the number of papers published on the quantum dots. As shown in Fig.1(b), the statistic indicates a threshold in the beginning of 1990's. This threshold is due to development of the Stranski-Krasntanow growth mode for forming the quantum dots. This emerging growth technique led to the first demonstration of an InAs quantum dot laser in 1994 by Technical University of Berlin, showing reduced temperature dependence of threshold current.



Fig.1: (a) A copy of the paper published in 1982 for the first proposal of semiconductor quantum dots (b) Evolution of the number of papers on quantum dots

There are two categories of concept to which the quantum dot devices belong to, as indicated in Fig.2. The first is quantum dot devices which utilize ensembles of quantum dots. For such devices, establishment of fabrication technologies of highly dense and highly uniform quantum dots is essential. The other category includes devices with single or individual quantum dots. Single photon emitters, single electron transistors, and quantum computing devices belong to this category.

Ensemble of quantum dots Indiv

Individual quantum dots



Fig.2. Quantum dot devices utilizing ensembles or individuals of quantum dots

### 3. Quantum dot devices in photonic network

Since the first demonstration of InGaAs quantum dot lasers in 1994, high performance lasing characteristics have been demonstrated, including low threshold current density of  $17A/cm^2$ , high T<sub>0</sub> up to 385K, and high differential gain at room temperature[2]. Figure 3 shows a trend of improvements of threshold current of quantum dot lasers. It should be noted that the lowest threshold current has been achieved in the quantum dot lasers. Furthermore, 1.3-µm lasing wavelength has been already achieved, which is significant for low-cost lasers for access network communication systems utilizing GaAs substrates. Many types of quantum dot vertical cavity surface emitting lasers (VCSELs) were also demonstrated. These results are promising for light sources in access and home/business local area network systems.

As indicted in Fig.4, in the next generation WDM/OTDM photonic network, quantum dot lasers and optical amplifiers will be key network nanodevices. To make the quantum dots be useful, fabrication of quantum dot lasers by MOCVD rather than MBE is significant for



Fig3: Progress in threshold current of quantum dot lasers



Fig.4: Quantum dot lasers and optical amplifiers will be implemented in future broadband photonic networks.

mass-production. Recently we succeeded in obtaining the lowest threshold current in MOCVD grown quantum dot lasers[3].

However, there still remain various issues to be solved in order to realize expected high-performance lasing characteristics such as high-speed modulation and zero-chirping effects. These include fabrication of quantum dots with high uniformity and high density. Moreover, understanding of carrier dynamics in the nanostructures for efficient carrier injection through the optimum design of quantum dots must be investigated. Narrower inhomogeneous broadening (<15mev) due to the size variation must be achieved, despite of the fact that typical inhomogeneous broadening is currently around 30meV. Recently, 1.52 µm emissions has been demonstrated from InAs quantum dots in In<sub>0.45</sub>Ga<sub>0.55</sub>As on GaAs substrates[4].

As an application of single quantum dots, single photon emitters are the most promising for quantum cryptography communications. It should be noted that nanostructures for light such as photonic crystal also play significant roles for nanophotonic devices. Moreover, coherent control of electronic states and spin in a single or coupled quantum dots will be important for quantum computation devices.

#### 4. Conclusion

We have discussed prospects of nanostructure devices focusing on quantum dot devices together with progress in fabrication and physics. Development of such nanostructure devices is a key to establish fundamental technology for future ubiquitous information society. From 2002, MEXT started a five-years national project focusing development of nanophotonic devices. The project is jointly operated with a METI project on photonic network devices. Both projects based on substantial collaboration between universities and industries are headed by Arakawa.

#### References

- (1) Y. Arakawa and H. Sakaki, Appl. Phys. Lett., vol. 40, pp. 939-941(1982).
- (2) Review of progress in quantum dot lasers is, for example, in the invited paper by Y. Arakawa, IEICE Trans. C, Vol.E85-C No.1pp.37-44 (2001)
- (3) J. Tatebayashi, N. Hatori, H. Kakuma, H. Ebe, H. Sudo, A. Kuramata, Y. Nakata, M. Sugawara, and Y. Arakawa, Electronics Letters, vol.39, No. 15, pp. 1130-1131(2003)
- (4) J. Tatebayashi, M. Nishioka, Y. Arakawa, Appl. Phys. Lett., vol. 78, pp. 3469-3471.(2001)