# A One-Kilobit PQR-CMOS Smart Pixel Array

Kwon-Seob Lim, Jung-Yeon Kim, Sang-Kyeom Kim,
Byeong-Hoon Park, and O'Dae Kwon

**The photonic quantum ring (PQR) laser is a three dimensional whispering gallery (WG) mode laser and has anomalous quantum wire properties, such as microampere to nanoampere range threshold currents and $\sqrt{T}$-dependent thermal red shifts. We observed uniform bottom emissions from a 1-kb smart pixel chip of a 32×32 InGaAs PQR laser array flip-chip bonded to a 0.35 μm CMOS-based PQR laser driver. The PQR-CMOS smart pixel array, now operating at 30 MHz, will be improved to the GHz frequency range through device and circuit optimization.**

**Keywords: Smart pixel array, photonic quantum ring, optical interconnection, VCSEL, flip chip bonding.**

Manuscript received Jan. 28, 2003; revised Oct. 8, 2003.

This work was supported by KOSEF, BK21, Samsung Co., and National Research Laboratory project of the Korean government.

Kwon-Seob Lim (phone: +82 31 279 5865, email: iflwy@postech.ac.kr), Jung-Yeon Kim (email: kukinine@postech.ac.kr), Sang-Kyeom Kim (email: kyeomi@postech.ac.kr), Byeong-Hoon Park (email: pbhae@postech.ac.kr) and O'Dae Kwon (email: odkwon@postech.ac.kr) are with the QPID Laboratory, Department of Electronics and Electrical Engineering, POSTECH, Pohang, Korea.

## I. Introduction

Research on free space optical switching and interconnection technology has been intensively investigated for the last decades [1]. One of the most important technologies in an optical interconnection is a so-called smart pixel, which incorporates a well-developed CMOS functional circuitry and optical devices such as a multiple quantum well modulator [2], vertical cavity surface emitting laser (VCSEL) [3], or photonic quantum ring (PQR) laser. As the size of a chip decreases and the operating frequency increases, crosstalk between two lines, impedance mismatching, and signal dispersion become unavoidable issues. Hence, flip-chip bonding and multi-chip module technologies have become common techniques for improving the interconnecting efficiency in high speed computing systems. The hybrid integration of VCSEL to the CMOS circuit has been a prevailing technique for up to 8×8 and 16×16 array chips. The PQR-CMOS combination is now more promising for lower power consumption and higher density smart pixel array development in kilo-to-mega chips.

In previous reports, we discussed a PQR laser [4]-[6] that exhibits ultra-low threshold currents and $\sqrt{T}$-dependent thermal spectral shifts, achieved from a toroidal micro-cavity of three dimensional (3D) whispering gallery (WG) modes in the peripheral Rayleigh band of the active multiple quantum well planes of a VCSEL-like structure. Cavity Q values of 15,000 or higher, observable from recent PQR devices due to their nearly perfect confinement in a 3D cavity, lead to unusual threshold currents far lower than the same size VCSELs or two dimensional WG lasers. These characteristics have allowed us to integrate a several kilobit PQR laser array so far and are promising for an even higher density array, which also makes the PQR laser a good candidate for laser display applications [7].

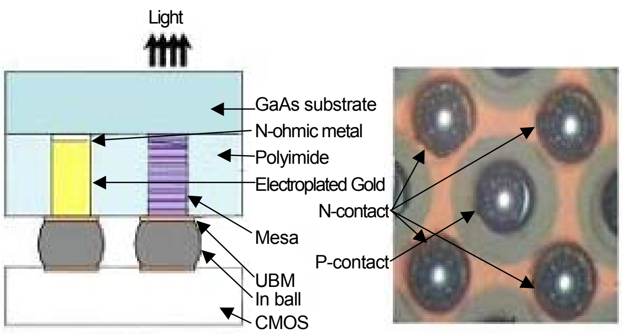
In this paper, we describe an independently addressable

CMOS repeater circuit to drive the PQR laser and pulse response of the PQR-CMOS smart pixel array. We also demonstrate a hybrid integration process for the 1-kb InGaAs PQR laser with the CMOS driver, particularly using double 32×32 In solder bumps by flip-chip bonding. Bottom emissions and modulation characteristics of the fabricated 1-kb PQR smart pixel array are also presented.

## II. Hybrid Integration

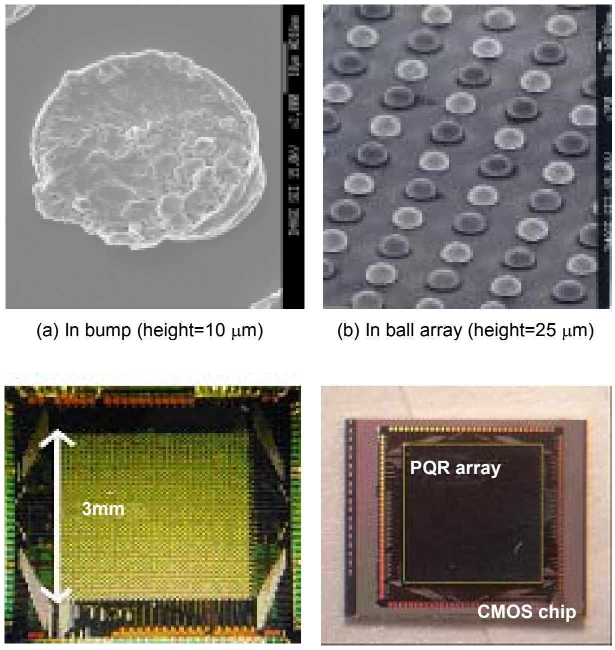
For fabrication of the bottom emitting PQR laser array, we chose an $In_{0.2}Ga_{0.8}As$ active layer whose photoluminescence has a maximum at a wavelength of 970 nm where the GaAs substrate becomes transparent. Mesas with a 15-μm diameter were formed by chemically assisted ion-beam etching to enhance the sidewall smoothness [8]. For the n-ohmic contacts in Fig 1, we evaporated AuGe/Ni/Au metals and accomplished rapid thermal annealing and then electroplated the Au posts above them up to the height of the mesa. After planarization with polyimide, the Cr/Ni/Au metals for the under bump metallurgy and In for the solder bump were evaporated as shown in Fig. 1(a). The p-contact mesa is effectively surrounded by four n-contacts, whose configuration may help the uniform spreading of carriers in the substrate region. In the process of In bump evaporation, the height of the In bump needs to be more than 10 μm. The larger the In ball size, the lower the probability of horizontal misalignments between the PQR and CMOS contacts. For this reason, we obtained a photo-resistor pattern as thick as 26 μm by using a viscous photoresist (AZ9260).

The GaAs substrate was lapped, thinned to 200 μm, and polished by using chemical mechanical polishing to reduce the attenuation loss substantially, since the light from the flip-chip-bonded PQR lasers are bottom-emitted through the substrate. Subsequently, we performed a reflow process on the hot plate



(a) (b)

Fig. 1. (a) The schematic layout of a PQR-CMOS smart pixel, (b) the optical microscope photograph of the PQR array with coplanar contact configuration.



(a) In bump (height=10 μm) (b) In ball array (height=25 μm)

(c) CMOS chip (d) Smart pixel chip

Fig. 2. The SEM images of (a) the In bump, (b) In ball array, (c) the optical microscope images of the fabricated CMOS chip, and (d) smart pixel chip.

at 200 °C for 2 minutes in an $N_2$ atmosphere. Figures 2(a) and (b) are scanning electron microscopy images of the In solder bump and In solder ball array before and after reflow, respectively. After reflow, the In bumps were changed into In balls due to the surface tension. The height of the In ball increased from 10 μm to 25 μm after reflow.

We also fabricated the CMOS driver chip by the MOSIS foundry service using TSMC-35-SIL technology. Each driver cell includes a selection circuit with column and row signals to independently address a particular cell in the 32×32 PQR laser array, flip-chip bonded to the CMOS chip at 40 °C for 2 minutes with a weight of 1.7 kg using a flip-chip bonder (M-8A, RD-automation). Figures 2(c) and (d) show the fabricated CMOS chip and smart pixel array.

## III. Properties of the PQR Laser Array

The PQR manifold for emission was naturally formed in the peripheral Rayleigh toroidal of the active region of a cylindrical mesa structure [4]-[7]. The images of Figs. 3(a) and (b) show the top and bottom emission. As shown in Fig. 4(a), the PQR laser exhibited ultra-low threshold properties that also indicated the same thresholds for either full or hollow (i.e., without central VCSEL region) mesa type PQRs approaching the theoretical predictions. PQRs of less than 7 μm began to enter the nano-ampere threshold regime [4]. To distinguish the PQR WG

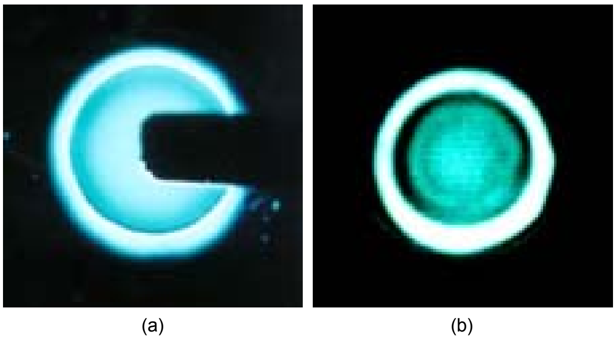



Fig. 3. Near field emission of PQR laser: (a) top (Φ=15 μm, I=10 μA), (b) bottom (Φ=15 μm, I=30 μA). The peripheral region is brighter than the central region.

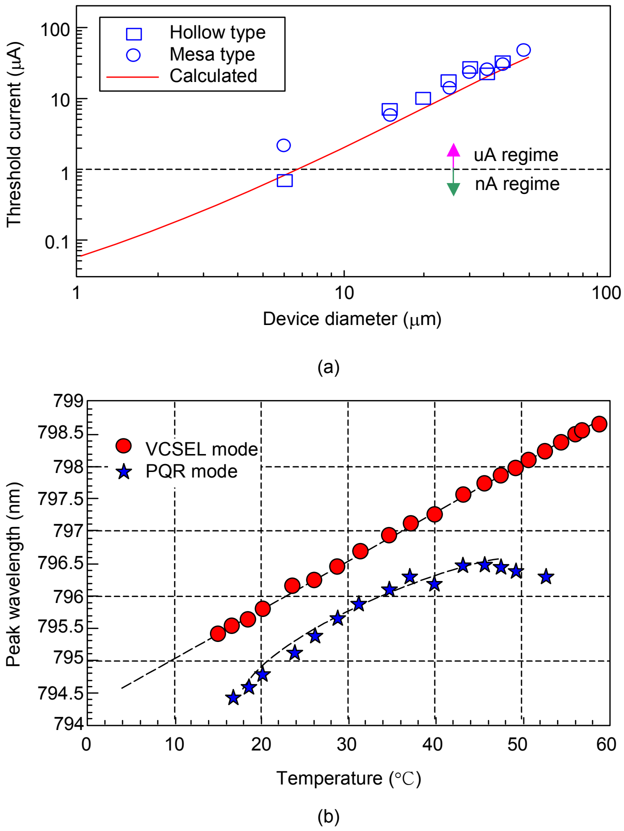



Fig. 4. Characteristics of the PQR laser: (a) threshold currents for the PQR laser as a function of the device diameter, (b) temperature dependent spectra. The best fits are given as $\lambda_{PQR}$=0.42 $(T-18)^{1/2}$ +793.4 (nm) and $\lambda_{VCSEL}$=0.07T+794.4 (nm).

mode from the VCSEL mode, we present the wavelength shift data for both as a function of the device temperature in Fig. 4(b). It is notable that the spectral shift of the PQR mode shows a distinct dependence, while the wavelength of the VCSEL mode increases linearly with a temperature coefficient of 0.07 nm/°C [9]. The level-off properties above 40 °C enabled us to integrate an array with a few kilobits for the PQR laser

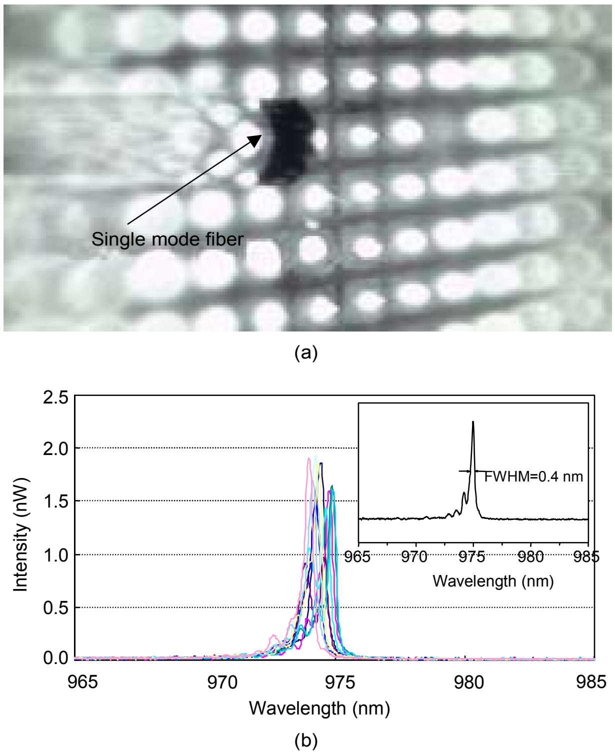



Fig. 5. (a) The charge coupled device image of some parts of the bottom emission. A single mode fiber tip of 8 μm in diameter is used for spectral measurement. (b) Bottom emission spectrums of 100 elements of the 1-kb PQR laser array. The inset shows that the line width of the fundamental mode is as narrow as 0.4 nm measured from a 15 μm device with a 100 μA injection current.

and are very promising for even higher-density smart pixel arrays. The 32×32 InGaAs PQR laser array employed here operates at a wavelength of 975 nm, emitting photons through the GaAs substrate bottom. Figure 5(a) shows clear bottom emissions of the 1-kb PQR smart pixel array at an injection current of 100 mA (about 100 μA per cell) and Fig. 5(b) is the superimposed bottom emission spectrum of 100 sampled elements out of the 1-kb PQR laser array.

The line width measured from the bottom emitting device with an optical spectrum analyzer (HP70951A) was as narrow as $\Delta\lambda_{1/2}$=0.4 nm at an injection current of 100 μA as shown in the inset of Fig. 5(b). Compared with that of a top emitting device ($\Delta\lambda_{1/2}$=0.05 nm [10]), the spectrum of the bottom emission was somewhat broader, probably because of interfacial scatterings on the substrate side which became the lower part of the effective toroidal cavity. The lower n-DBR stack interfaces and the buffer-substrate interface may be rougher than the p-DBR side due to the rough wafer surface. The N-side semiconductor may also have a lot more dislocation defects during epitaxial growth. We suspect that the bottom emission may correspond to a resonant PQR cavity effectively

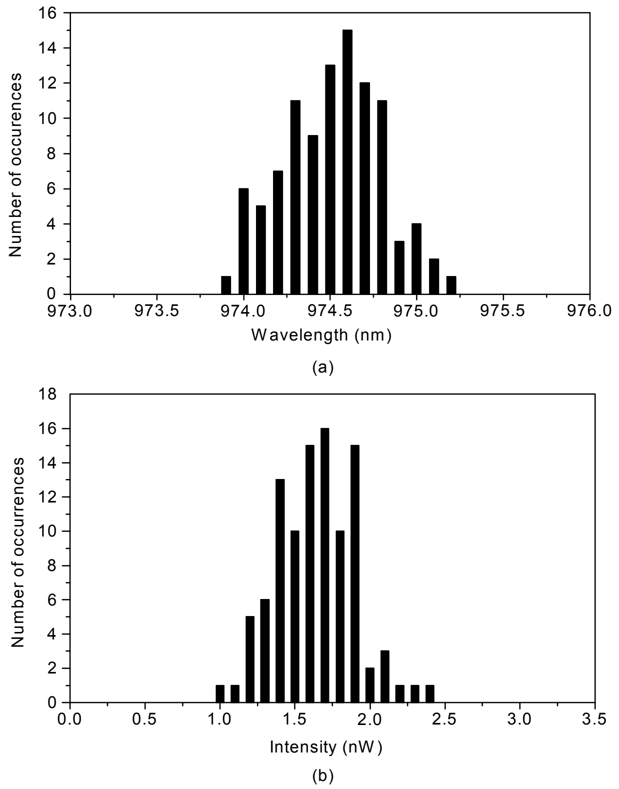



Fig. 6. (a) The histogram of the lasing wavelength and (b) the intensity of the 1-kb InGaAs PQR laser array.

Table 1. The average and standard deviation of the lasing wavelength and intensity of the bottom emission of the 1-kb InGaAs PQR laser array.

| | Wavelength (nm) | Intensity (nW) |
|---|---|---|
| Average | 974.50 | 1.64 |
| Standard deviation | 0.28 | 2.60 |

different from the top emission Fabry-Perot path. The lasing wavelength and intensity distribution of the 1-kb PQR laser array is shown in Figs. 6(a) and (b). The lasing wavelength was 974.5 nm ± 0.7 nm, while the intensity collected through the probe tip of the optical spectrum analyzer was 1.7 nW ± 0.7 nW on average. The average and standard deviation of the lasing wavelength and intensity of the bottom emission of the 1-kb InGaAs PQR laser array are presented in Table 1. The sharp, uniform bottom emissions from the PQR smart pixel arrays are very promising for the massively parallel optical interconnection technology.

## IV. Large Signal Modulation

The CMOS drive circuits allowed each PQR to be independently modulated by external electrical control. Figure 7

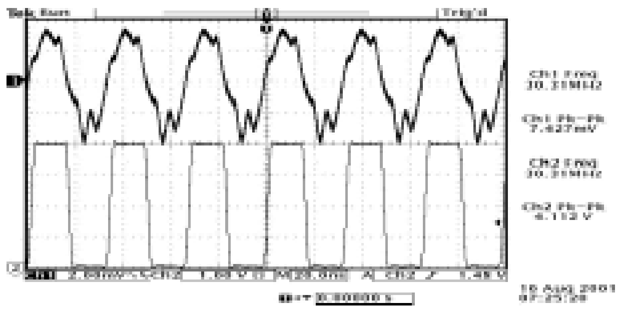


Fig. 7. Large-signal modulation characteristics of the 1-kb PQR-CMOS smart pixel (input: ch2, output: ch1).

shows the large-signal modulation characteristics of the PQR-CMOS smart pixel array packaged in a 64-pin ceramic package. The PQR emissions were coupled to the optical fiber probe of an InGaAs photo-detector, and the generated signals were analyzed in a digital oscilloscope. The detector was an InGaAs-APD whose relative sensitivity was below 50 percent of the maximum at a wavelength of 975 nm. The present PQR smart pixel array operates with a modulation speed of 30 MHz corresponding to an aggregate throughput of 60 Gbps with 2 bits/Hz, 1 kb cells, and 100 μA/cell currents.

This modest result originates mainly from the parasitic effects of the ceramic package, large-size bonding pad, In ball, and the equipment itself [11]. The modulation characteristics of the PQR laser, however, will be greatly improved not only by a proper design of the PQR laser and an optimized process to reduce RC time constants but also by a small signal modulation instead of the large signal modulation [12]. With a given value of R=300 Ω and C=1.8 pF, f=1/2 πRC (a PQR with a 7.5 μm radius) becomes 300 MHz. The present modulation experiment, however, gives rise to a measurement limitation: the oscilloscope probe's capacitance of 8pF limits the value of f = 66 MHz. In addition, ceramic package parasitics seemed to have affected our data significantly.

## V. Conclusions

Ultra-low threshold currents and $\sqrt{T}$-dependent thermal spectral red shifts of the PQR laser lead us to the hybrid integration of the PQR-CMOS smart pixel array which is promising for very high density arrays with low power consumption and robust spectral behavior. We fabricated a 1-kb PQR laser array and a 0.35 μm CMOS-based PQR laser driver, flip-chip bonded together via the 1-kb In ball array. We obtained uniform distribution of the lasing wavelength and intensity of the bottom emission of the 1-kb InGaAs PQR laser array. The PQR-CMOS smart pixel array works with a frequency of 30 MHz corresponding to an aggregate throughput of 60 Gbps. With an optimized design of the PQR laser and measurements, we can further improve the high speed operation property for free space optical interconnection and optical computing.

## References


[1] A.V. Krishnamoorthy and K.W. Goossen, "Optoelectronic-VLSI: Photonics Integrated with VLSI Circuits," *IEEE J. Select. Topics Quantum Electronics*, vol. 4, 1998, pp. 899-912.

[2] A.L. Lentine, K.W. Goossen, J.A. Walker, L.M.F. Chirovsky, L.A. D'Asaro, S.P. Hui, B.J. Tseng, R.E. Leibenguth, J.E. Cunningham, W.Y. Jan, J.-M. Kuo, D.W. Dahringer, D.P. Kossives, D.D. Bacon, G. Livescu, R.L. Morrison, R.A. Novotny, and D.B. Buchholz, "High-Speed Optoelectronic VLSI Switching Chip with >4000 Optical I/O Based on Flip-Chip Bonding of MQW Modulators and Detectors to Silicon CMOS," *IEEE J. Select. Topics Quantum Electronics*, vol. 2, 1996, pp. 77-83.

[3] R. Pu, C. Duan, and C.W. Wilmsen, "Hybrid Integration of VCSEL's to CMOS Integrated Circuits," *IEEE J. Select. Topics Quantum Electronics*, vol. 5, 1999, pp. 201-208.

[4] J.C. Ahn, K.S. Kwak, B.H. Park, H.Y. Kang, J.Y. Kim, and O'Dae Kwon, "Photonic Quantum Ring," *Phys. Rev. Lett.*, vol. 82, 1999, pp. 536-539.

[5] J.C. Ahn, H.Y. Kang, and O'Dae Kwon, "Angle-Dependent Multiple-Wavelength Radial Emissions in a Toroidal Microcavity:(A Photonic Quantum Ring Laser), " *Proc. SPIE Conf. Physics and Simulation of Optoelectronic Device VI*, vol. 3283, 1998, pp. 241-251.

[6] B.H. Park, J.C. Ahn, J. Bae, J.Y. Kim, M.S. Kim, S.D. Baek, and O'Dae Kwon, "The Evanescent and Propagating Wave Characteristics of the Photonic Quantum Ring Laser," *Appl. Phys. Lett.*, vol. 79, 2001, pp. 1593-1595; B.H. Park, J. Bae, M. J. Kim, and O'Dae Kwon "Chiral Wave Propagation Manifold of the Photonic Quantum Ring Laser," *Appl. Phys. Lett.*, vol. 81, 2002, pp. 580-582.

[7] Kwon-sub Lim, Jung-yeon Kim, Byeong-hoon Park, and O'Dae Kwon, Jungchak Ahn, and Oh-hyun Kwon, "1K·bit Smart Pixel Array Using the Photonic Quantum Ring Laser Array," *Conf. Optical Internet/Photonics in Switching*, July 21-25, 2002, Korea, pp. 166-168.

[8] J.Y. Kim, K.S. Kwak, J.S. Kim, B.K. Kang, and O'Dae Kwon, "Fabrication of Photonic Quantum Ring Laser Using Chemically Assisted Ion Beam Etching," *J. Vacuum Sci. Technol. B*, vol. 19, 2001, pp. 1334-1338.

[9] G.W. Taylor and P.A. Evaldsson, "Temperature Dependent Operation of the Vertical Cavity Surface Emitting Laser," *IEEE J. Quantum Electronics*, vol. 30, 1994, pp. 2262-2270.

[10] J. Bae, B.H. Park, J.Y. Kim, and O'Dae Kwon, "Photonic Quantum Corral, Carrier Ordering, and Photonic Quantum Dot/Ring Device," *Institute of Physics Conference Series*, 2001.

[11] H. Kosaka, K. Dutta, K. Kurihara, Y. Sugimoto, and K. Kasahara, "Gigabit-Rate Optical-Signal Transmission Using Vertical-Cavity Surface-Emitting Lasers with Large-Core Plastic-Cladding Fibers," *IEEE Photon. Technol. Lett.*, vol. 7, 1995, pp. 926-928.

[12] S.M.K. Thiyagarajan and A.F.J. Levi, "Dynamic Behavior of Scaled Microdisk Lasers," *Solid-State Electronics*, vol. 45, 2001, pp. 1821-1826.



**Kwon-Seob Lim** received his BS degree in electronic engineering from Ajou University in 2001, MS degree in electronic engineering from Pohang University of Science and Technology (POSTECH), Pohang, Korea, in 2003. His research interests include smart pixel array, flip-chip bonding, and the fabrication and characterization of the photonic quantum ring laser. Since 2003, he has been at Modem System Lab., Telecommunication Network, Samsung Electronics Co., Ltd.



**Jung-Yeon Kim** received the BS degree in electronic engineering from Pusan National University, Busan, Korea, in 2001, and the MS degree in electronic and electrical engineering from POSTECH in 2003. Her research interests include CMOS design and CMOS Image Sensor. After her graduation, she joined Samsung Electronics Co., Ltd.



**Sang-Kyeom Kim** received the BS degree in electronic and electrical engineering from Kyungpook National University, Daegu, Korea, in 2002. He is currently working toward the MS degree in electronic and electrical engineering at POSTECH. His main research topic is smart pixel array using PQR array.



**Byeong-Hoon Park** received the BS degree from Kyungpook National University in 1995, and the MS and PhD degrees from POSTECH, Pohang, Korea, in 1997 and 2002, all in electronic engineering. His research interests include high power laser diode arrays, CMOS design, and the fabrication and characterization of the photonic quantum ring laser. Since 2002, he has been at Photonics Solution Lab., in Samsung, where his current activities are in the area of semi-cooled electro-absorption modulator-integrated DFB laser (EML) for 40 km transmission in metro communication applications.

**O'Dae Kwon** is a Professor at POSTECH and Head of the National Research Laboratory for VLSI-Photonic IC. He received the BS degree in electronic engineering from Seoul National University, Seoul, Korea, in 1969, and the MS degree (1975) and PhD degree (1978) in electrical engineering from Rice University. He joined POSTECH in 1986 and organized a new semiconductor optoelectronics group, developing the first MOCVD-grown SEED switching device. In 1997, he invented a photonic quantum ring (PQR) semiconductor laser based on photonic quantum corral and trapping effects, and won the Scientist of the Year 1998 Award in Korea. He is a member of the American Physical Society of Korea, and senior member of IEEK and KIEE.