Tunable multi-wavelength quantum dot external-cavity lasers

Chen-Hung Pai and Gray Lin*
Department of Electronics Engineering and Institute of Electronics,
National Chiao Tung University, 1001 University Road, Hsinchu 300-10, Taiwan

ABSTRACT

The chirped multilayer quantum-dot (QD) gain media are arranged in Fourier-transform external-cavity laser (FT-ECL) configuration. Novel slit designs select 2, 3, and 4 different wavelengths that are diffracted from the grating for optical feedback. Therefore, the dual-, triple- and quadruple-wavelength ECLs are demonstrated in this study. The resulted multi-wavelength lasing emissions are achieved under injected current of 100 mA (or 1.33 kA/cm^2) with signal to amplified spontaneous emission (ASE) ratio over 20 dB. Around peak-gain wavelength of 12xx-nm range, the adjacent wavelength separation is over 50 nm for dual-wavelength lasing, up to 13 nm for triple-wavelength lasing, and about 4-5 nm for quadruple-wavelength lasing emissions. To further extend the wavelength separation for dual-wavelength lasing emissions, another modified scheme with two separate external mirrors are adopted and the achieved maximum value is about 126 nm in wavelength separation or over 25 THz in frequency difference. The terahertz (THz) generation by photomixing of dual-wavelength ECLs is also discussed in this study.

Keywords: tunable lasers, external-cavity lasers, quantum-dot lasers, semiconductor lasers

1. INTRODUCTION

External-cavity lasers (ECLs) incorporated with semiconductor gain media are promising for novel light sources. The widely tunable and multi-wavelength feature of ECLs has great potentials for coarse wavelength-division multiplexing (CWDM) in fiber-optic communications. Moreover, photomixng of multi-wavelength ECLs [1] has made possible the compact, cost-effective, and tunable THz generation in many applications such as spectroscopy, medical imaging, and security. To achieve simultaneously multi-wavelength lasing with semiconductor lasers, the common approaches are utilizing single laser with physically separated gain media for each wavelength [2] or multiple lasers in the external cavity [3]. However, these approaches require elaborate fabrication and packaging procedures which lead to larger dimension of the external cavity system.

The largest wavelength separation of dual-wavelength operation with quantum-well (QW) gain medium has been achieved by Huang *et al*. in grating-coupled external cavity [4]. Nevertheless, ECLs with QW gain medium require very high injection current density (typically more than 10kA/cm^2) to populate carriers to higher energy state for broadband tuning. Consequently, QD gain medium is a better choice since it can fulfill both low injection current density and broad spectral-tuning requirements [5-8]. Furthermore, low injection current density is also beneficial for cost and power consumption issues.

In this work, chirped multilayer QD structure of 1.3μm wavelength range [9] is incorporated in two modified schemes of Littman ECL configuration. In the first configuration, dual-, triple-, and quadruple-wavelength lasing emissions as well as their continuous tuning are demonstrated at record low injection current density of 1.33 kA/cm^2. Then in the second configuration, the maximum wavelength separation of 126 nm is achieved for dual-wavelength ECL by independent control of the optical feedback. Finally, we discuss the laser characteristics of dual-wavelength ECLs as well as their terahertz (THz) generation by photomixing.

2. EXPERIMENTAL DETAILS

The QD laser structure is grown by molecular beam epitaxy on Si-doped GaAs substrate. The active region consists of 10 layers of self-assembled InAs QDs which are capped by $In_{0.15}Ga_{0.85}As$ layers of varying thickness and spaced by GaAs of 33 nm. Three chirped wavelengths of longer, medium, and shorter wavelength range, with stacking numbers of 4, 3 and 3 layers, are designed with InGaAs layer thickness of 4, 3 and 1.5 nm, respectively. The detailed layer structure can be found in [9]. The wafer is processed into ridge waveguides of 5-μm width. As-cleaved laser bars are then

Nonlinear Optics and Applications VII, edited by Mario Bertolotti, Joseph Haus, Alexei M. Zheltikov,
Proc. of SPIE Vol. 8772, 87720V · © 2013 SPIE · CCC code: 0277-786X/13/$18 · doi: 10.1117/12.2017500

passivated with broadband anti-reflection coating (R < 1%) in the front facets as well as high-reflection distributed Bragg reflector coating (R > 99%) in the rear facets.

Figure 1 shows the light-current-voltage (*L-I-V*) characteristics of solitary AR/HR coated QD laser with 1.5 mm in cavity length. The lasing wavelength of as-cleaved QD lasers is 1260 nm; however, it moves to shorter wavelength 1180 nm after AR/HR coating due to the increased mirror loss. In addition, the threshold current dramatically increases from 20mA to 100mA.

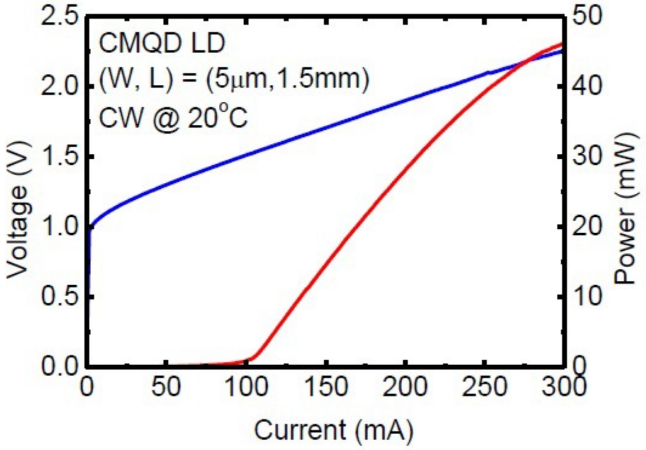

Figure 1. *L-I-V* characteristics of solitary AR/HR coated QD laser with 5-μm width and 1.5-mm length.

The AR/HR coated QD lasers are investigated in the Fourier-transform external-cavity laser (FT-ECL) configuration, i.e. the first modified scheme of Littman configuration by insertion of Fourier lens and slit in the first-order diffracted path [3]. Figure 2 shows the experimental setup. A collimating lens is utilized to collect the divergent light from the front mirror facet. The optical feedback is provided by first-order diffraction light which is diffracted from an external grating and then collected by a lens focused onto an external mirror. To select the multi-wavelength lasing emissions, a V-like slit is designed and put between Fourier lens and external mirror. The external grating is with groove density of 1200 lines/mm and blazed at wavelength of 1.0 μm. To tune the center wavelength or change the wavelength separation, one can move the V-like slit vertically or horizontally. The zeroth-order diffracted light is coupled via a multimode optical fiber into an optical spectrum analyzer.

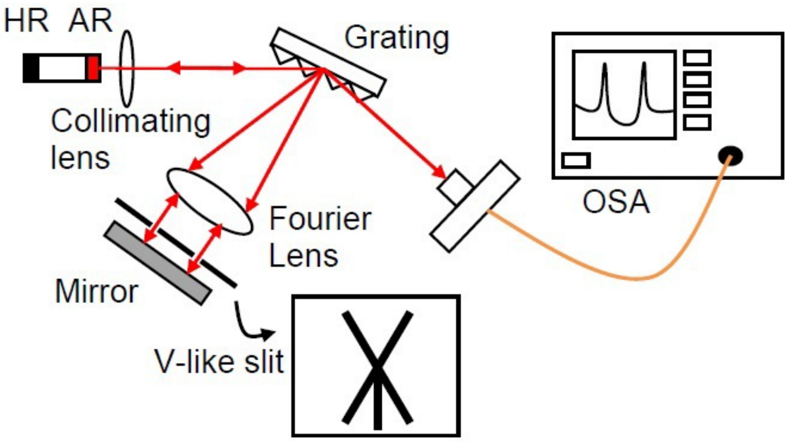

Figure 2. Experimental setup of tunable FT-ECL configuration.

Concerned to two-color ECLs, several concept schemes are proposed in the literature [10]. In above modification scheme, increasing the adjacent wavelength separation means increased spatial separation of selected wavelengths, which is limited by the slit design. However, the two separate wavelengths may be too far away to make nonzero incidence to the end mirror, and results in poor optical feedback. Therefore, the second modification scheme of Littman configuration, termed double-Littman ECL, is adopted and shown in Figure 3. Only two separate end mirrors are utilized for independent control of optical feedback. Since neither Fourier lens nor slit aperture is introduced, it is hard to get small wavelength separation due to the large physical dimension of end mirrors. The maximum wavelength separation achieved in this work is demonstrated by this scheme.

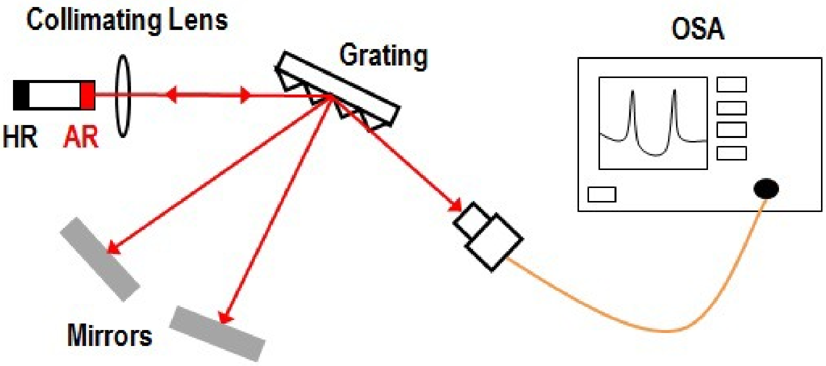

Figure 3. Experimental setup of double-Littman ECL configuration.

3. RESULTS AND DISSICUSIONS

3.1 Multi-wavelength FT-ECLs

Figure 4 shows the dual-wavelength tuning spectra under injection current of 100 mA at heatsink temperature of 20 ^{0}C. The signal to ASE ratio is in the range of 20 to 40 dB. The wavelength separation over 86 nm or frequency difference of 17 THz (not shown) can be achieved in FT-ECL configuration and it is limited by our design of slit separation. To further increase the wavelength separation may render the nonzero incidence of two selected wavelengths. Therefore, single end mirror should be replaced with two end mirrors or the second modification scheme of double-Littman ECL should be adopted.

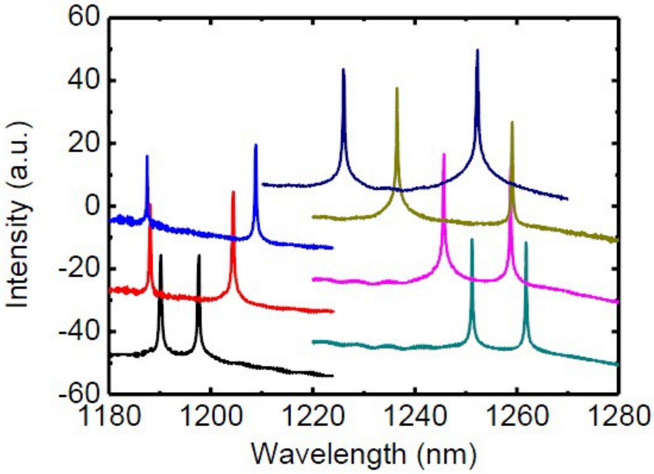

Figure 4. The dual-wavelength lasing spectrum in FT-ECL configuration.

Figure 5 shows the triple- and quadruple-wavelength lasing emissions. Continuously triple-wavelength tuning is obtained by utilizing the lower part of V-like slit as shown in Figure 2. The slit design can operate as a switch from two wavelengths to three wavelengths. The maximum adjacent wavelength separation is 13 nm and the signal to ASE ratio is also larger than 20 dB. With different slit design, the quadruple-wavelength lasing emissions is demonstrated and shown in Figure 5(b). The adjacent wavelength separation is about 4 nm; however, the intensities of four wavelengths vary in a large range. This phenomenon results from uneven optical feedbacks between these four wavelengths.

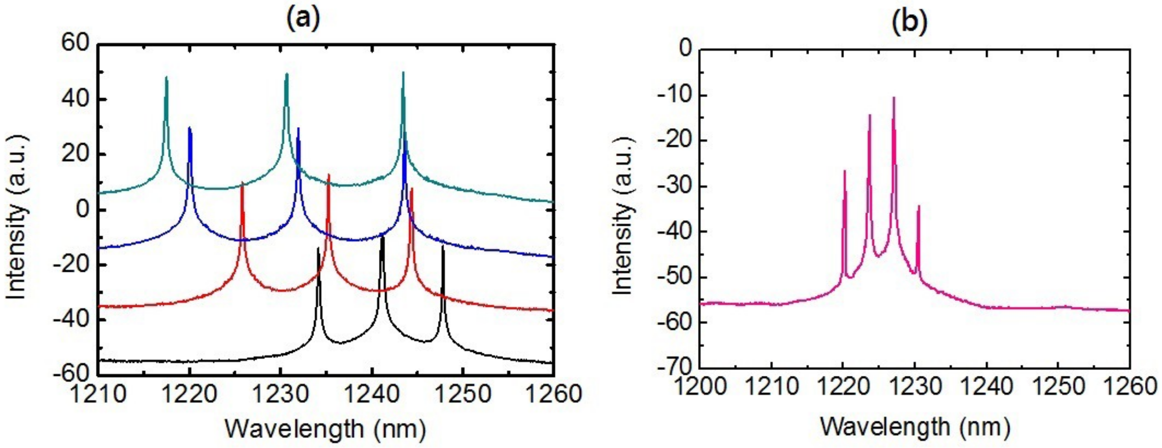

Figure 5. The spectrum of (a) triple-wavelength lasing emission (b) quadruple-wavelength lasing emission in FT-ECL configuration.

3.2 Double-Littman ECLs

Since the wavelength separation in FT-ECL configuration is limited by the slit, the double-Littman ECL configuration is adopted to achieve dual-wavelength lasing emission. Figure 6 shows the dual-wavelength lasing spectrum measured in double-Littman ECL configuration. The maximum wavelength separation or frequency difference is about 126 nm or over 25 THz. This result is in reasonable agreement with our maximum tuning range of 132 nm (from 1148 nm to 1281 nm) in conventional Littman configuration. The signal to ASE ratio is over 20 dB even at maximum wavelength separation as shown in Figure 6.

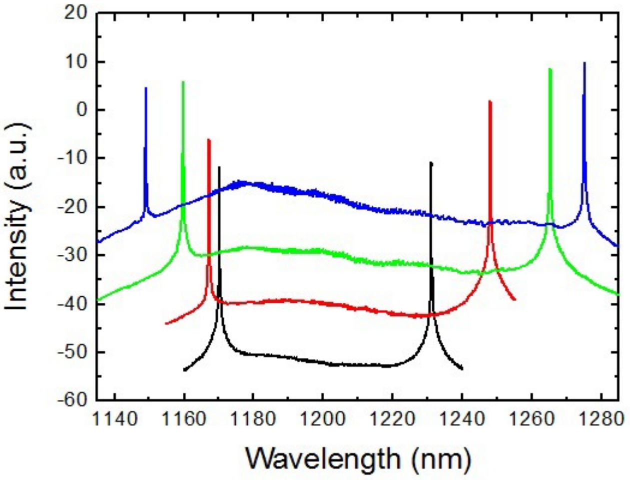

Figure 6. The dual-wavelength lasing spectrum in double-Littman ECL configuration.

The optical intensity distribution between the two wavelengths is an interesting issue in dual-wavelength lasing emissions. Matus *et al.* have theoretically analyzed the dynamics of various two-color ECL configurations by studying their time dependence of optical intensity distribution [11]. Here we present the static *L-I-V* characteristics of dual-wavelength lasing emissions in double-Littman ECL configuration. We first generate dual-wavelength lasing emissions of equal intensities with wavelength separation of 46 nm (1169nm and 1215nm) and then collect the total optical power of zeroth-order diffracted light. As shown in Figure 7, the current dependence of optical power seems to exhibit certain oscillating periodicity which needs further investigation.

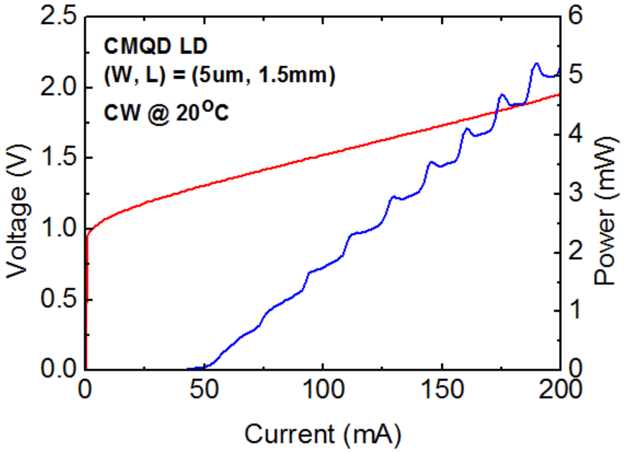

Figure 7. The *L-I-V* characteristics of dual-wavelength in double-Littman ECL configuration.

3.3 THz generation

Multi-wavelength ECLs are promising for THz generation by photomixing of multi-wavelength lasing emissions. Matus *et al.* have identified and characterized five two-color lasing regimes of coherent, semicoherent, multimode, chaotic, and multimode chaotic operation by numerical simulation of several two-color ECL configurations [11]. They have concluded that the two-color coherent laser regime should be the most attractive one for THz signal generation [11] and later demonstrated experimentally in FT-ECL configuration [14]. Moreover, direct THz emission out of dual-wavelength ECLs is investigated by Wang *et al.* [13] and Hoffmann *et al.* [14]. Figure 8 shows our photomixing setup for THz generation. The dual-wavelength lasing emissions is monitored by OSA and focused onto a biased photoconductive antenna (PCA). An aspheric focusing Si lens is mounted on the back side to collect wide-angel emission THz wave radiating from the PCA. The focused THz wave is then detected by the bolometer. Since the bolometer cannot discriminate the emitted THz signal from any other far infrared radiation (e.g. heat radiation) from the laser diode [12], we are going to confirm it by Fourier Transform Infrared Spectrometer (FTIR) of Bruker IFS 66v/S.

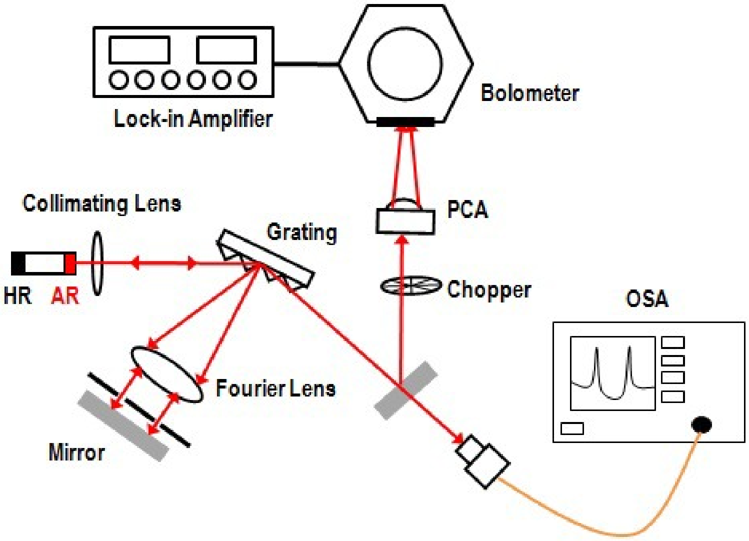

Figure 8. The photomixing setup for generating THz radiation with FT-ECL.

4. SUMMARY

Tunable multi-wavelength light emitters based on InAs/InGaAs/GaAs QDs are demonstrated in this study. The chirped multilayer QD gain media are arranged in FT-ECL configuration, i.e. the first modified scheme with Fourier lens and slit introduced in the first-order diffracted path. Novel slit designs with 2, 3, and 4 slit apertures select different wavelengths that are diffracted from the grating for optical feedback. Therefore, the dual-, triple- and quadruple-wavelength ECLs are implemented for promising applications, such as wavelength-division multiplexing (WDM) in fiber-optic communications and THz light sources generation by difference-frequency generation (DFG) mechanism.

The resulted multi-wavelength lasing emissions are achieved under injected current of 100 mA (or 1.33 kA/cm2). Around peak-gain wavelength of 12xx-nm range, the adjacent wavelength separation is over 50 nm for dual-wavelength lasing, up to 13 nm for triple-wavelength lasing, and about 4-5 nm for quadruple-wavelength lasing emissions. The maximum wavelength separation is limited by our slit design while the minimum wavelength separation is determined by the slit width. Moreover, the signal to ASE ratio is over 20 dB. Application of coarse-WDM or even dense-WDM can be benefited from further optimization.

To further extend the wavelength separation for dual-wavelength lasing emissions, the second modified scheme of double-Litman ECL configuration with two separate external mirrors are adopted and the maximum achieved value is about 126 nm in wavelength separation or over 25 THz in frequency difference. The terahertz (THz) generation by photomixing of dual-wavelength ECLs is also discussed in this study.

ACKNOWLEDGMENT

The authors are indebted to K. F. Lin of Industrial Technology Research Institute (ITRI) for device fabrication. The growth of QD laser structure is credited to Innolume GmbH in Dortmund, Germany. This work was supported by the Ministry of Education under the Aiming for the Top University and Elite Research Center Development Plan as well as the National Science Council Project under the contract number NSC 101-2221-E-009-122 and NSC 101-3113-P-009-004.

REFERENCES

[1] Gu, P., Chang, F., Tani, M., Sakai, K., and Pan, C. L., "Generation of Coherent cw-Terahertz Radiation Using a Tunable Dual-Wavelength External Cavity Laser Diode," Jpn. J. Appl. Phys. 38(11A), 1246-1248 (1999).

[2] Poguntke, K. R., Soole, J. B. D., Scherer, A., LeBlance, H. P., Caneau, C., Baht, R., and Koza, M. A., "Simultaneous multiple wavelength operation of a multistripe array grating integrated cavity laser," Appl. Phys. Lett. 62(17), 2024-2026 (1993).

[3] Breede, M., Hoffmann, S., Zimmermann, J., Struckmeier, J., Hofmann, M., Kleine-Ostmann, T., Knobloch, P., Koch, M., Meyn, J. P., Matus, M., Koch, S. W., and Moloney, J. V., "Fourier-transform external cavity lasers," Opt. Commun. 207(1-6), 261-267 (2002).

[4] Huang, C. C., Cheng, C. H., Su, Y. S., and Lin, C.F., "174-nm mode spacing in dual-wavelength semiconductor laser using nonidentical InGaAsP quantum wells, " IEEE Photon. Technol. Lett. 16(2), 371-373 (2004).

[5] Tabuchi, H. and Ishikawa, H., "External grating tunable MQWlaser with wide tuning range of 240 nm,"Electron. Lett. 26(11), 742-743 (1990).

[6] Seltzer, C. P., Bagley, M., Elton, D. J., Perrin, S., and Cooper, D. M., "160 nm continuous tuning of an MQW laser in an external cavity across the entire 1.3μm communication window," Electron. Lett. 27(1), 95-96 (1991).

[7] Varangis, P. M., Li, H., Liu, G. T., Newell, T. C., Stintz, A., Fuchs, B., Malloy, K. J., and Lester, L. F., "Low-threshold quantum dot lasers with 201 nm tuning range," Electron. Lett. 36(18), 1544-1545 (2000).

[8] Biebersdorf, A., Lingk, C., De Giorgi, M., Feldmann, J., Sacher, J., Arzberger, M., Ulbrich, C., Böhm, G., Amann, M.-C., and Abstreiter, G., "Tunable single and dual mode operation of an external cavity quantum-dot injection laser," J. Phys. D Appl. Phys. 36(16), 1928–1930 (2003)

[9] Lin, G., Su, P. Y., and Cheng, H. C., "Low threshold current and widely tunable external cavity lasers with chirped multilayer InAs/InGaAs/GaAs quantum-dot structure," Opt. Express 20(4), 3941-3947 (2012).

[10] Friedrich, C.-S., Brenner, C., Hoffmann, S., Schmitz, A., Mayorga, I.C., Klehr, A., Erbert, G., and Hofmann, M.R., "New Two-Color Laser Concepts for THz Generation," IEEE J. Quantum Electron. 14(2), 270-276 (2008).

[11] Matus, M., Kolesik, M., Moloney, J. V., Hofmann, M., and Koch, S. W., "Dynamics of two-color laser systems with spectrally filtered feedback," J. Opt. Soc. Am. B 21(10), 1758-1771 (2004).

[12] Hoffmann, S. and Hofmann, M., "Generation of terahertz radiation with two color semiconductor lasers," Laser Photon. Rev. 1(1), 44-56 (2007).

[13] Wang, C. L. and Pan, C. L., "Tunable multiterahertz beat signal generation from a two-wavelength laser-diode array," Opt. Lett. 20(11), 1292-1294 (1995).

[14] Hoffmann, S., Hofmann, M., Kira, M., and Koch, S. W., "Two-colour diode lasers for generation of THz radiation," Semicond. Sci. Technol. 20(7), 205-210 (2005).