Tuning of Detection Wavelength in a Resonant-Cavity-Enhanced Quantum-Dot-Embedded Photodiode by Changing Detection Angle *

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We have fabricated a resonant-cavity-enhanced photodiode (RCE-PD) with InGaAs quantum dots (QDs) as an active medium. This sort of QD-embedded RCE-PD is capable of a peak external quantum efficiency of 32% and responsivity of 0.27 A/W at 1.058 μm with a full width at half maximum (FWHM) of 5 nm. Angle-resolved photocurrent response eventually proves that with the detection angle changing from 0° to 60°, the peak-current wavelength shifts towards the short wavelength side by 37 nm, while the quantum efficiency remains larger than 15%.

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Nd:YAG lasers have been deployed in wide applications including industrial manufacturing, medicine, remote sensing, space communications and weapon guidance. The common choices of photodiodes for light detection in such systems are silicon photodiodes (PDs) or InGaAsInP-based avalanche photodiodes (APDs). Unfortunately, the wavelength of Nd:YAG laser, 1.064 μm, falls in the "sensitivity valley" between the long-wavelength limit of the spectral response of Si-PDs and the short-wavelength limit of the spectral response of InGaAs/InP-PDs. To fill in this gap, resonant-cavity-enhanced (RCE) p-i-n PDs with quantum-dot (QD) absorption layers were reported, operating near 1.3 and 1.06 μm with peak quantum efficiency of 65%.[1] This kind of RCE-PDs, in which Nd:YAG laser systems are used as laser sources, will be beneficial for many applications.

However, as is well known, the wavelength of RCE-PDs is determined by both the cavity spacer length and the thickness of the so-called quarter-wavelength layers, which form the distributed Bragg reflector (DBR) of the microcavity. In reality, it is very difficult to make both as-grown layer structures and processed devices operate at the exact wavelength of 1.064 μm. Thus, there is demand for a method of tuning the detection wavelength of the RCE-PD in situ, as it is employed. Changing environment temperature or using the MEMS method may be one of choices for the wavelength tuning. However, it is either too inconvenient or too complicated to use in real applications.

In the present study, we demonstrate that the detection wavelength of a resonant- cavity-enhanced photodiode (RCE-PD) can easily be tuned by rotating it with respect to the incident irradiation, as is first verified by angle-resolved transmission spectroscopy or by photoluminescence (PL) spectroscopy near resonantly excited at different angles with a 1064 nm laser beam. To exploit the potential in real applications, we have fabricated RCE-PDs with InGaAs quantum dots as an active medium. This sort of QD-embedded RCE-PD is capable of a peak external quantum efficiency of 32% and responsivity of 0.27 A/W at 1.058 μm with a full width at half maximum (FWHM) of 5 nm. The angle-resolved photocurrent response eventually proves that with the detection angle changing from 0° to 60°, the peak-current wavelength shifts towards the short wavelength side by 37 nm, while the quantum efficiency holds larger than 15%.

The structure of QDs microcavity with $\mathrm{In}_{0.5}\mathrm{Ga}_{0.5}\mathrm{As}$ self-assembled quantum dots (SADs) as the active medium was grown on a (100)-oriented n-doped GaAs substrate by molecular beam epitaxy (MBE) in an EPIGEN II system. A nominally $3\lambda/2$-thick cavity spacer layer was sandwiched between the bottom (n-doped) and top (p-doped) distributed Bragg reflector (DBR) mirrors, which consist of 19 and 15 pairs of quarter-wavelength ($\lambda/4$) GaAs/AlAs layers, respectively. Two groups of three stacked layers of $\mathrm{In}_{0.5}\mathrm{Ga}_{0.5}\mathrm{As}$ SADs (each was formed by 5 monolayers of $\mathrm{In}_{0.5}\mathrm{Ga}_{0.5}\mathrm{As}$ SADs) were embedded at two antinodes of the planar cavity. All the layers were grown at 600°C except that the growth temperature for SADs was lowered to 500°C. A wedged cavity for the sake of tuning cavity-wavelength was achieved

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by stopping the substrate rotation during the MBE growth of the spacer layer, while two DBR mirrors were all grown under the rotation. As a result, the resonant frequency of the cavity-mode varies as the detect point moves away from the centre of the wafers.

In our usual measurement of angle-resolved photoluminescence,[2] the sample was mounted in a liquid-nitrogen (77 K) cryostat. The 488-nm line of an Ar^+ laser was used for the excitation of PL. The PL emission is collected by an optical fibre set at the angle θ and at 20 cm apart from the sample. The fibre set could be slide along a semicircular track. The PL emitted light was dispersed by the Dilor SuperLabram monochrometer, and detected by a liquid-nitrogen-cooled CCD detector.

The proposal for selectively detecting the irradiation of different wavelengths by an RCE-PD comes from the well-known fact that the photon mode in an empty microcavity has an in-plane dispersion if the propagation of the light beam is not normal to the plane,[3,4] as described simply by

$$E_{ph} = (c\hbar/n)[(m\pi/l_z)^2 + k_{\|}^2]^{1/2}, \quad m = 1, 2, \cdots, \quad (1)$$

where $k_{\|} = k\sin\theta$ with k being the wave number in free space; m is the index of the normal cavity mode; c, n, and l_z are the light speed, refractive index of the cavity, and the cavity length in the grown direction, respectively; θ is the incident angle inside the cavity spacer. In our case, $l_z = 3\lambda/2$, and E_{ph} can be rewritten in the following form:

$$E_{ph} = (\hbar c/n)(3\pi/L_z)(1 - \sin^2\theta_a/n^2)^{-1/2}, \quad (2)$$

where θ_a is the detection angle for the outgoing light beam in the air. To testify the above idea, the angle-resolved PL spectra of $\mathrm{In}_{0.5}\mathrm{Ga}_{0.5}\mathrm{As}$ SADs microcavity, which had an identical layer structure as the present one except that it was neither n-type nor p-type doped, were previously measured at 77 K.[2] With the increasing detection angle from 0° to 62°, the detected PL peak shifted continuously towards the short wavelength by 40 nm in accordance with the above expression. From the device point of view, in the present work, we verify how the peak-detection wavelength of a pin RCE-PD can be tuned by simply changing the detection angle.

In Fig. 1, curve *a* shows the PL spectrum of naked $\mathrm{In}_{0.5}\mathrm{Ga}_{0.5}\mathrm{As/GaAs}$ SADs measured at 300 K from the reference sample, which was grown under the same condition as a completed pin RCE-PD except that the top p-type DBR was in absence. It displays a typical Gaussian-shaped line, peaking at the wavelength of 1064 nm with a full width at half maximum (FWHM) of 55 nm. Curve *b* shows the reflectivity spectrum measured from the pin RCE-PD sample. There is a dip showing up at the wavelength of 1073 nm near the centre of the stop-band (the broad spectrum region of the high reflectivity as seen in the figure). Obviously, this cavity mode falls in the envelop of the PL spectrum of naked $\mathrm{In}_{0.5}\mathrm{Ga}_{0.5}\mathrm{As/GaAs}$ SADs so that a reasonable responsivity can still be ensured for the RCE-PDs. Curve *c* shows the normal incident PL spectrum of the same sample, which is centred at the same wavelength of 1073 nm as the cavity mode, with a full width at half maximum of less than 1 nm.

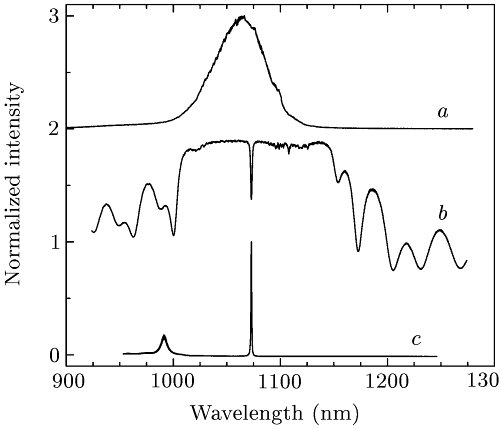

Fig. 1. (a) PL spectrum of naked $\mathrm{In}_{0.5}\mathrm{Ga}_{0.5}\mathrm{As/GaAs}$ SADs (b) reflectivity spectra of and (c) PL spectra of the quantum-dot-embedded semiconductor microcavity.

Figure 2 shows a full set of angle-resolved transmission spectra measured at the room temperature by using the similar setup that was previously used in the measurement of the angle-resolved PL spectra. As seen in the insert of Fig. 2, a tungsten-halogen projection lamp was used as the incident light source, and fixed on a slider which can slide along the semicircular track. The sample was mounted on a clamp, and placed at the centre of the semicircular track with its normal direction fixed at 0°. The transmitted light was collected and sent into a Dilor SuperLabram spectroscope. In the measurement, the incident light could be changed from 0° to 70°. As shown in the insert of Fig. 2, with increasing the incident angle θ from 0° to 55°, a continuous blue-shift from 1042 nm to 1008 nm has also been observed in consistency with the result of the angle-resolved PL spectra measured previously. While the transmission decreases and the FWHM increases as the angle increases. This may be attributed to the deterioration in the cavity finesse at the large detection angles. It is interesting to notice that doublets with a splitting of 0.8–3 nm appear as long as the incident angle is larger than 35°. By polarization measurements, one became aware of that the observed doublet stemmed from TE–TM mode splitting. It is considerable that the deviation of the cavity-mode frequency from the central frequency of the stop band can make the TE and TM modes split more discernibly. The inhomogeneous broadening in optical spectra of self-assembled quantum dots gives the TE and TM cavity-modes a chance to show up in optical spectra simultaneously.[2]

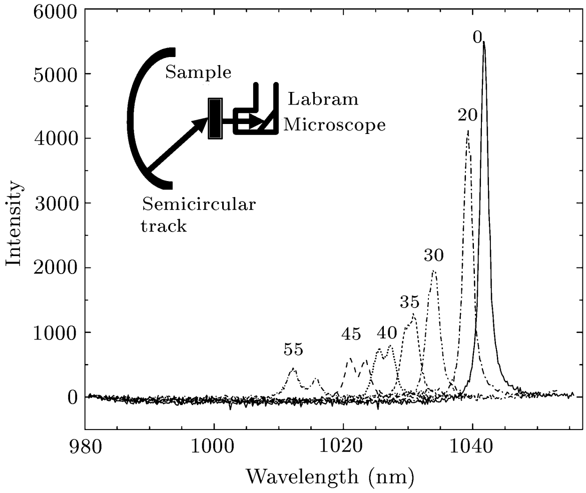

Fig. 2. Angle-resolved transmission spectra of the quantum-dot-embedded semiconductor microcavity. Insert: schematic diagram of the measurement equipment.

In order to obtain information how the RCE-PD works when changing the incident light angle for the sake of tuning the detection wavelength, we use the 1.064 μm YAG laser beam as the excitation of PL. The PL emission is collected by the optical fibre set, which is located 20 cm apart from the sample. During the measurement the fibre set was fixed at the angle of 0°, and the incident angle of the 1.064 μm excitation beam could vary from 0° to 65° by sliding it along the semicircular track. The results are shown in Fig. 3. As the incident angle increases from 0° to 22°, there is no spectrum feature detected at the wavelength range we concern. The intense signal on the short wavelength side is caused by the near-resonant excitation of the wavelength 1064 nm. When the angle of the incident light turns to 24°, we could clearly see a signal peaking at the wavelength 1073 nm, with the FWHM of about 1 nm. However, with the further increase of the incident angle above 24°, the peak disappears again, whose physical reason is quite straightforward. According to Eqs. (1) and (2), the cavity mode changes its wavelength from 1073 nm to 1064 nm when we turned the incident angle of the excitation light from 0° to 24°. Only at this point is the wavelength 1064 nm of the incident light exactly in resonance with the cavity mode. Such resonant absorption by the cavity excites the active medium of QDs inside the cavity, and causes the PL signal to emit. At any other angle larger than 24°, the incident light will be totally reflected by the high-reflectivity forbidden band, as seen in curve *b* of Fig. 1. This experiment shows that the mechanism of tuning the wavelength of the RCE detector by changing the detection angle works very well.

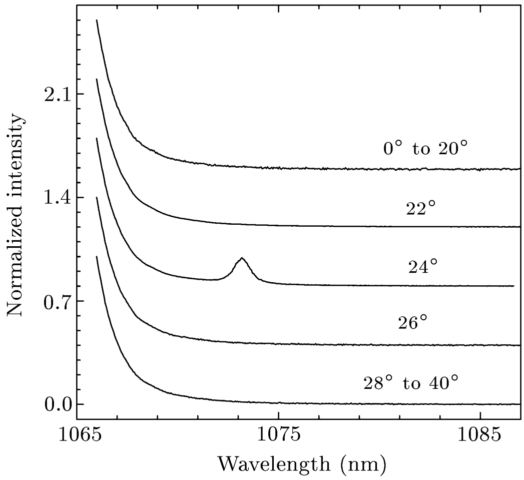

Fig. 3. Angle resolved PL spectra of the quantum-dot-embedded semiconductor microcavity excited near the resonance by a 1064-nm laser beam with the incident angle changing from 0° to 40° in steps of 2°.

In order to test the above-mentioned tuning mechanism in a ready-to-use RCE-PD with QDs as the active medium, the standard photolithography, wet chemical etching, and mesa processes were employed for fabricating the RCE-PD, and the ohmic contact was formed by Au evaporation. For optical measurements, the device was of $130 \times 140\,\mu\mathrm{m}^2$ with the circle optical window of 50 μm diameter opened.

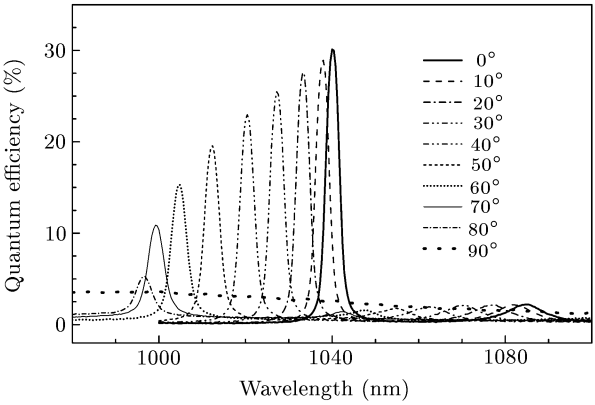

Fig. 4. Quantum efficiency of the device with the detection angle changing from 0° to 90°.

The completed devices have showed excellent diode characteristics with typical dark current values of about $10^{-15}\,\mathrm{A}/\mu\mathrm{m}^2$ at zero bias. Photocurrent responses were carried out in the wavelength range of 900–1200 nm. As the light source, tungsten–halogen projection lamp was guided through a single-pass spectroscope. The output of the spectroscope was coupled to a multimode fibre, and then delivered onto the optical window of the device by a microscope system. The fabricated device was mounted on a probe station, which could be rotated to change the detection angle. The quantum-efficiency was measured by using phase-locked detection and a calibrated InGaAs photodiode. The peak external quantum efficiency of 32% and responsivity of 0.27 A/W at 1.058 μm have been achieved with the FWHM of 5 nm, as shown in Fig. 4.

To tune the wavelength of the detector, the photocurrent responses were measured as a function of the detection angle in Fig. 4. It is clear that with the detection angle changing from 0° to about 80°, the peak-current wavelength shifts from 1040 nm to 996 nm. While the peak quantum efficiency decreases from 30% to 5% and the FWHM increases from 3.5 to 4.5 nm. In real applications, a tuning as large as 37 nm by tilting the detection angle to 60° should be sufficient to grasp 1064 nm irradiation from a Nd:YAG laser for a processed RCE-PD with a peak-detection wavelength slightly longer than 1064 nm (quantum efficiency holds a reasonable level larger than 15%).

In summary,[5−8] we have demonstrated that the detection wavelength of a resonant-cavity-enhanced photodiode (RCE-PD) can easily be tuned by rotating it with respect to the incident irradiation, as was first verified both by angle-resolved transmission spectroscopy and by photoluminescence spectroscopy nearly resonant-excited at different angles with 1064 nm laser beam. To exploit its potential in real applications, we have designed and fabricated a resonant-cavity-enhanced pin photodiode with multi-stacked QDs as the absorption layers operating at 1064 nm. This sort of QD-embedded RCE-PDs is capable of a peak external quantum efficiency of 32% and responsivity of 0.27 A/W at 1.058 μm with the FWHM of 5 nm. Eventually, angle-resolved photocurrent response proves that with the detection angle changing from 0° to 60°, the peak-current wavelength shifts towards the short wavelength side by 37 nm, while the quantum efficiency holds larger than 15%. This feature should be sufficient to in situ grasp 1064 nm irradiation from a Nd:YAG laser for a processed RCE-PD with a peak-detection wavelength slightly longer than 1064 nm.

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