

Reviews

Progress of quantum-dot photoelectronic devices

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Abstract Quantum-dot photoelectronic devices are quantum-dot lasers, quantum-dot infrared photodetectors, quantum-dot single-photon sources and quantum-dot optical memory designed and fabricated using quantum-dot microstructures as active regions of the devices, and they have potential applications in optical communication, optical informational process and optoelectronic computer. In this paper, recent progress on the fabricated methods and operating properties of these photoelectronic devices are reviewed, and new developed directions of the field are also predicated.

Keywords: quantum-dots; self-assembling growth; photoelectronic devices; operating performances

1 Introduction

Semiconductor photoelectronic devices have important functions in the optical informational technology, they can achieve the creation, transmission, process, memory and display of the light. So far, various photoelectronic devices fabricated by using semiconductor quantum-wells act as active regions have obtained widely applications in the photoelectronic technology. However, rapidly development of informational photonic technology requires new photoelectronic devices with superior photoelectronic properties.

Recently, quantum-dots (QDs) photoelectronic devices are currently attracting a great deal of attention due to their unique photoelectronic properties, relative to quantum well structures, so that they have potential applications in the optical communication, photoelectronic computer and optical informational process^[1-4]. In this paper, we review the development of quantum-dot photoelectronic devices in recent 3–5 years, and new developed tendency of the research field is also predicated.

2 Quantum-dot lasers

Owing to their zero-dimensional properties, such as

strongly quantum confined effects and squeezed state density, quantum-dot laser structures are expected to present improved characteristics compared to bulk or quantum-well devices. In the recent past, very low threshold current density, chirpless operation, temperature insensitive, and high-power laser emission have been reported.

The utilization of self-assembled InAs quantum dots grown on GaAs has extended the lasing wave length at 1.3 μm . In order to improve the laser performance, the use of reasonable device structures is very important. LIU *et al*^[5] fabricated a 1.3 μm multilayer InAs quantum-dot lasers using a high growth temperature GaAs spacer layer. The spacer layer inhibits threading dislocation formation, resulting in enhanced electrical and optical characteristics. 1.3 μm emitting devices have extremely low room-temperature threshold current densities of $\sim 35 \text{ A/cm}^2$ and with operation up to 105°C. Tunnel injection is very effective in suppressing hot-carrier and achieving high-speed modulation of 1.3 μm quantum-dot lasers^[6]. This is due to the carriers are injected by tunneling in the quantum-dot lasing states and thus they do not heat other carriers or phonons as much, resulting in reduced carrier leakage from the active region and recombination in the cladding layer. As a result, the characteristic temperature is en-

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hanced and the differential gain increases ($dg/dn \approx 1 \times 10^{-14} \text{ cm}^2$), leading to enhanced modulation bandwidth ($f_{-3\text{dB}}=11 \text{ GHz}$). In addition, in order to achieve high-speed modulation, require to realize a quantum-dot laser with a high modal gain. Amano *et al* [7] reported the characteristics of $1.3 \mu\text{m}$ quantum-dot lasers with high-density and high-uniformity of $8.0 \times 10^{10} \text{ cm}^{-2}/\text{Sheet}$. It is demonstrated that the modal gain of $1.3 \mu\text{m}$ quantum-dot lasers is about 43 cm^{-1} at room temperature, and full width at half maximum (FWHM) of the photoluminescence spectra of this lasers is as narrow as 23 meV .

InAs nanostructures grown on an InP substrate exhibit the improved optical properties at $1.55 \mu\text{m}$ wavelength, because of a lower lattice mismatch (3.2%) compared to InAs/GaAs (7%). Many authors have investigated the formation of InAs quantum dots on InP substrate and their emitting properties of $\sim 1.55 \mu\text{m}$. Allen *et al* [8] fabricated the tunable InAs quantum-dot laser on (100) InP wafer. Stimulated emission between $\sim 1.51 \mu\text{m}$ and $\sim 1.64 \mu\text{m}$ was observed depending on the cavity length and the quantum dot barrier height. The threshold current density was as low as 49 A/cm^2 at 77 K . The relation between temperature and lasing peak wavelength was measured to be $\sim 0.21 \text{ nm/K}$ leading to room temperature lasing at $\sim 1.61 \mu\text{m}$. A high-gain and low-threshold InAs quantum-dot laser on InP had been achieved by Caroff *et al* [9]. Laser emission on the ground-state transition ($\lambda=1.59 \mu\text{m}$) is obtained at room temperature, the threshold current density is as low as 190 A/cm^2 . Ground-state modal gain and transparency current density is measured to be 7 cm^{-1} and 23 A/cm^2 per dot layer, respectively. The improved InAs/InP quantum-dot laser performances are very promising for the realization of high-frequency modulated laser and optical amplifier working at the $1.55 \mu\text{m}$ optical telecommunication wavelength. Recently, Michon *et al* [10] studied the structural and optical properties of self-assembled InAs quantum-dots directly grown on InP (001) by low pressure metalorganic vapor-phase epitaxy. The photoluminescence exhibited an intense peak centered around $1.58 \mu\text{m}$ at room temperature, and presented a FWHM of 65 meV .

The mode-locking of the laser diodes by active and passive modulation of cavity loss is a well-developed technique for the generation of picosecond to subpicosec-

ond optical pulses in the near-infrared spectral range. Rafailov *et al* [11] have demonstrated mode-locking at a 21 GHz pulse repetition frequency from a two-section quantum-dot laser where the pulse duration can be either in the picosecond or femtosecond domains. The experimental data show that pulse as short as 390 fs can be generated directly from such quantum-dots. The first external cavity mode-locked quantum-dot two-section laser is reported [12]. It is found that the mode-locked pulses have strong linear chirp, enabling an order of magnitude compression ultrashort pulse of 1.2 ps width and a pulse energy of 1.46 pJ , implying a peak power of 1.22 W .

The achievement of high quality factor (Q) is very important for high quantum efficiency. Muller *et al* [13] reported a quantum-dot vertical-cavity surface-emitting laser. Cavity quality factors as high as 33000 , and ground state lasing is demonstrated with a single quantum-dot active layer for temperatures up to $\sim 110 \text{ K}$. Shin *et al* [14] have designed and fabricated high-Q photonic crystal heterostructure cavities formed in InGaAsP suspended membranes. The highest Q value is greater than 100000 . The lasing wave lengths of the cavity are 1444 and 1577 nm when incident threshold pump powers around 3.5 and 4.2 mW , respectively.

3 Quantum-dot infrared photodetectors

In the past few years, quantum-dot infrared photodetectors have emerged as promising devices for long wavelength infrared detection due to their potential advantages over the conventional quantum well infrared photodetectors. The advantages include: (1) intrinsic sensitivity to normal incident infrared light, (2) longer lifetime of excited electrons due to greatly suppressed electron-phonon scattering, and (3) the predicted significantly lower dark current. These unique properties arise from strongly three-dimensional carrier confinement of quantum dots.

At present, the active region structures used for quantum-dot photodetector are mainly InAs/GaAs or InGaAs/GaAs quantum dots formed by self-assembled growth methods. Kim *et al* [15] fabricated the lateral quantum-dot infrared photodetectors utilizing uniform-sized InAs quantum dots. The absorption spectrum showed an absorption peak corresponding to the intersubband transition at

around 10 μm , which can be operated at room temperature. A high-sensitivity $\text{In}_{0.6}\text{Ga}_{0.4}\text{As}/\text{GaAs}$ quantum-dot infrared photodetector with detection wave band in 6.7~11.5 μm and operating temperature up to 260 K under normal incident illumination has been demonstrated [16]. The peak detection wavelength shifts from 7.6 to 8.4 μm when the temperature rises from 40 to 260 K. The high operating temperature is attributed to the very low dark current and long carrier lifetime in the quantum dots of this device. Recently, the properties of a tunneling quantum-dot infrared photodetector operating at room temperature have been studied by Bhattacharya *et al* [17]. The device displays two-color characteristics with photoresponse peak at ~6 μm and ~17 μm . The extremely low dark current density of 1.55 A/cm² at 300 K for 1 V bias is made possible by the tunnel filter. In particular, JIANG *et al* [18] reported a two-stack multi-color quantum-dot infrared photodetector for detection in the 8~12 μm spectral window. The normal incident responsivities were found to be 4.52×10^9 and 2.06×10^9 cm²·Hz/W when the photodetected wavelength were 8.4 and 10.6 μm at the temperature of 40 K, respectively.

The high cost of fabricating of III-V photoreceivers prevents their acceptance in these applications. Si-based technology provides a very encouraging option to implement monolithic photoreceivers used for gigabit-rate data transmission with the benefits of low cost, high reliability, and mature manufacturability. A Si resonant-cavity-enhanced photodiode was fabricated on a silicon membrane. The photodiode has an external quantum efficiency of 33.8% at the resonant wavelength of 848 nm and a full width at half maximum of 17 nm. The responsivity was 4.6 times that of a conventional Si p-i-n photodiode with the same absorption layer thickness [19]. Moreover, LIN *et al* [20] demonstrated a high-performance, tensile-strained Ge p-i-n photodetector on Si platform with an extended detection spectrum of 650~1605 nm and a 3 dB bandwidth of 8.5 GHz measured at $\lambda=1040$ nm. Since its high speed, broad detection spectrum and compatibility with Si-CMOS technology, this device is attractive for applications in both telecommunications and integrated optical interconnects.

Conjugated polymers, nanocrystal quantum dots, and their composites have attracted the attention of researchers

for the development of optoelectronic devices, such as light-emitting diodes, photovoltaics, and optical information memory. QI *et al* [21] have realized highly efficient photodetectors based on composites of the semiconducting polymer poly [2-methoxy-5-(2'-ethoxyhexyloxy)-1,4-phenylenevinylene] and PbSe nanocrystal quantum dots. The external quantum efficiency in these devices is greater than 1 for electric fields $E \sim 7 \times 10^5$ V/cm. The observed photocurrent gain could be attributed to the carrier multiplication in PbSe nanocrystal quantum dots via multiple exciton generation, and the efficient charge conduction through the host polymer material. McDonald *et al* [22] reported the photoconductivity at infrared wavelengths of 975~1300 nm, from a polymer/nanocrystal quantum dot composite. The photocurrent is attributed to absorption in the nanocrystals with subsequent hole transfer to the polymer and had an internal quantum efficiency of $\sim 5 \times 10^{-6}$ to $\sim 10^{-5}$ charges/photon at 5 V bias.

4 Quantum-dot single-photon devices

Single-photon devices, such as single-photon source and single-photon detector, have attracted considerable interests because of their potential applications in the quantum cryptography communications and quantum computations.

Quantum dots are attractive as single-photon sources because they are relatively stable, have narrow spectral linewidths and high radiative decay rates, and can be integrated into microcavities—to improve the collection efficiency. A quantum-dot excited on resonance by a pulsed source can have an extremely small probability of generating two photons in the sample pulse. Santorin *et al* [23] tested the indistinguishability of photons emitted by a self-assembled InAs quantum dot in a microcavity. The result indicates that consecutive photons are largely indistinguishable, with a mean wave-packet overlap as large as 0.81, making this source useful in a variety of experiments in quantum optics and quantum information. Laurent *et al* [24] reported the spontaneous emission of a single quantum embedded in a two-dimensional photonic crystal cavity. The resonant coupling between the dot and the strongly localized optical mode significantly shortens the spontaneous emission lifetime, so that the coherence time of the emitted

photons is dominated by radiative effects. The emitted photons are indistinguishable, with a mean wave-packet overlap as high as 72%.

A planar semiconductor cavity can be used to enhance the efficiency from an electrically driven single InAs/GaAs quantum-dot [25]. The photon statistics change can be observed when the injective current is modified. The observed bunching of photons from the bisection state can be explained by the presence of charged state within the quantum dot with lifetime greater than 4 ns. Single photon emission from both the excitation and biexcitation states is demonstrated under electrical injection. Zwiller *et al* [26] developed a technique to obtain single quantum dots at the edge of sharp GaAs tips. The dots are shown to have a narrow emission linewidth and the single-quantum emitter nature was demonstrated by antibunching measurements. It is shown that these tip structures with stable single photon emitters at their apex can be used as probes for further controlled experiments in quantum and nano-optics. Furthermore, Hennessy *et al* [27] fabricated a strongly coupled single quantum dot cavity system, and found that the generated photon stream becomes antibunched in this system, proving that the strongly coupled exciton/photon system is in the quantum regime. In comparison to devices containing multiple quantum dots, the single quantum dot cavity has significantly higher quality factors, ranging from 12000 to 30000. The observations unequivocally show that quantum information tasks are achievable in solid-state cavity quantum electrodynamics.

Single-photon detection schemes based on sensitive and ultrafast optical quantum detectors gain their dominance in various single photonics applications. Korneev *et al* [28] have measured the quantum efficiency and noise-equivalent power of nanostructured NbN superconducting single-photon detectors in the visible to infrared radiation range. The device exhibited an experimental quantum efficiency of up to 20% in the visible range, and noise-equivalent power varies from $\sim 10^{-17}$ W/Hz^{1/2} for 1.55 μm photons to $\sim 10^{-20}$ W/Hz^{1/2} for visible radiation. More recently, Hees *et al* [29] present a systematic study of the effect of InAs deposition-time on single-photon detectors based on quantum-dot resonant tunneling diodes. In a photon counting experiment a detection efficiency of 3.7%

has been determined. With a small decrease in counting efficiency to 2.0% a low dark count rate of less than 6.6×10^{-10} ns⁻¹ can be achieved.

5 Summary

To achieve good performance of the quantum-dot photoelectronic devices, such as high efficient light-emission of the quantum-dot lasers, sensitive responsivity of the quantum-dot infrared photodetectors and rapidly single-photon emission of the single-photon sources, one first needs to achieve self-assembling growth of high-uniformity nanocrystallites and quantum dots, which is a key problem that how to fabricate practical quantum-dot photoelectronic devices. Secondary, the devices structures need to be optimistically designed. In fact, quantum cavity, photon bandgap crystals, strongly coupled single quantum dot system as well as multilayer quantum dots have obtained successive applications in various quantum-dot optoelectronic devices. Third, the relationships between structural characteristics and operating properties should be theoretically studied, so that we can deepen understanding for novel physical properties of the quantum dot microstructures.

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