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Invited

Future Prospects of Opto-Electronic Devices and Processings

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We review the current status, hightlighting the recent new important developments, and examine the future prospects of epitaxial growth technologies and opto-electronic devices. A more detailed view is given in the SUMMARY section.

1. INTRODUCTION

In this paper, we review the current status and examine the future prospects of epitaxial growth technologies and opto-electronic devices. The review will only highlight the most recent important new developments instead of trying to be exhaustive. A complete reference is also not permitted due to limited space.

2. EPITAXIAL GROWTH

After two decades of research and development, MOVPE is now an important and thriving commercial activity. It has been particularly successful in producing optical devices, especially in phosphorus containing compounds such as GaInAsP and AlGaInP. For electronic devices, although very substantial progress has been made in GaAs/AlGaAs systems, the production of highly uniform heterostructures in thickness, composition and doping in a reproducible manner remains a great challenge, especially for GaInAsP materials. Such difficulty is inherently due to the lack of ability to precisely control the varying flow patterns and complicated gas-phase reactions inside the reactor. In addition, since the MOVPE reactor chamber is usually a rather small enclosure for the substrate, serious competition of material deposition occurs between the walls and the substrate, resulting in changing alloy compositions for thick layers. Yet, as MO-VPE continues to move into the production environment this paramount need to achieve reproducibly very uniform alloys and doping concentrations will be an ever increasingly important issue. In addition, the extremely large consumption and waste treatment of toxic gases such as arsine and phosphine in the factory environment, especially for low-pressure MO-VPE processes, will also be of great safety concern.

Similarly, MBE also has undergone two decades of intensive research and development. It has proven to be an extremely valuable growth technique for investigating new materials, physics, and devices. For GaAs/AlGaAs, it has been very successfully employed for the production of high performance, low noise FETs, and about 45% of the entire world supply of compact disc lasers. Its strength lies in its superior layer thickness and composition uniformity control made possible by the beam nature and real-time in-situ growth diagnoses. However, MBE is completely helpless in preparing phosphorus containing materials. Gas-source MBE was developed as an intermediate solution by replacing solid arsenic and phosphorus with arsine and phosphine while keeping the conventional solid group III sources. Future development of MBE will focus on multi-wafer production machines, microwave FETs, and 0.98 μm strained layer InGaAs/AlGaAs lasers. Gradually, MBE will be accepted as a common manufacturing technique as MBE-phobia disappears among the production people.

Bridging the gap between the currently established techniques of MO-VPE and MBE is Chemical beam epitaxy (CBE). CBE is essentially an MO-VPE process conducted in a high-vacuum growth chamber. In essence, it combines the versatility of the vapor sources of MO-VPE together with the molecular beam properties of MBE. As a result, it is seen to be a powerful technique for both the crystal growers and the device designers. The use of metalorganic compounds has stimulated research into growth mechanisms. The crucial knowledge that is emerging is helping not only CBE, but also MO-VPE, and is now being fed back into the choice and design of new precursors. Very significant advances continue to be made in CBE. For example, carbon doping up to 10^{21} cm^{-3} is achieved in GaAs by simply using trimethylgallium. This is a capability very unique to CBE. Using such heavily doped carbon base, 10 Gb/s HBT decision circuits are fabricated from CBE-grown GaAs/AlGaAs heterostructures using trimethylamine alane as the Al starting source (Abernathy, AT&T Bell Labs). Very rapid progress in CBE-grown opto-electronics (Tsang, AT&T Bell Labs) is made. Long wavelength (1.5 μm) InGaAs/InGaAsP GRINSCH quantum well lasers have threshold current densities as low as 170 A/cm^2, internal quantum efficiency of 83% and internal waveguide los of 3.8 cm^{-1}. At 1.3 μm, high performance InGaAsP/InP MQW buried heterostructure lasers emitting around 1.3 μm were prepared. At 20°C, CW threshold currents were 5-8 mA and quantum efficiences were 0.35-45 mW/mA for 250 μm long lasers having once facet ~85% reflective coated. At 80°C, the CW threshold currents remained low, 23 mA, quantum efficiency stayed high, 0.22 mW/mA, and output power of ~10 mW was achieved. CW power output as high as 125 mW was achieved with 750 μm long lasers having AR-HR (~ 5%-85%) coatings. More importantly, these QW laser wafers have thickness uniformity < ± 1% and peak photoluminescence wavelength < ± 5 nm (as good as ± 1.5 nm) across the entire 2 inch diameter wafer. Very high quality Bragg reflectors of GaInAsP/InP (~ 11.5 μm thick) are also successfully prepared by CBE demonstrating the excellent stability of growth process in contrast to MO-VPE for growing thick quarternary layers. Mirrors with nearly 100% reflectivity and with more than 400 Å flat top region in the Bragg band around 1.55 μm have been achieved by using 45 pairs of InP (1348 Å) and InGaAsP (1216 Å, λ_g = 1.45 μm) quarter wavelength layers. A monolithic p-i-n/HBT transimpedance photoreceiver circuit operated up to 5 Gb/s and a sensitivity of -18.8 dBm is successfully fabricated from CBE-grown InGaAs/InP materials. Truly selective area epitaxy with no deposition over the SiO_2 masks has been routinely obtained with excellent epilayer morphology.

3. DEVICE PROGRESS

Very significant new developments continue to occur in the field of opto-electronic devices and integrations. These include long wavelength (1.3 - 1.5 μm) lattice-matched and strained-layer (SL) InGaAsP MQW lasers, 0.98 μm strained-layer InGaAs/AlGaAs QW lasers, highly linear analog lasers, visible (≤ 0.65 μm) AlGaInP lasers, wavelength tunable lasers, colliding-pulse mode-lock lasers, vertical cavity surface emitting lasers, and high-performance OEIC's.

In GaAs/AlGaAs system, QW lasers have almost completely replaced the double heterostructure (DH) lasers. In particular, GRINSCH lasers have offered superior device performance. Recently, GRINSCH lasers were also quite extensively studied in long wavelength InGaAs(P)/InP systems. One of the important topics in this area is the strained-layer QW lasers. 1.5 μm GRINSCH SL $In_xGa_{1-x}As$/InGaAsP 1.2 - 1.8% compressive strained (x = 0.7 - 0.8) and 0.9 - 1.6% tensile strained (x = 0.4 - 0.3) QW lasers were prepared by low-pressure MO-VPE. For single QW lasers, a minimum threshold current density of 160A/cm^2 was obtained (Thijs, Philips). Such value was also obtained with CBE-grown GRINSCH SQW lasers (Tsang, AT&T Bell Labs). CW output powers was as high as 325 mW for AR/HR coated MQW devices. Tensile strained MQW lasers operated CW up to 140°C. With HR-HR coated lasers, submilliampere-threshold 1.5 μm SL MQW lasers were achieved (Temkin, AT&T Bell Labs; Zah, Bellcore). Aging tests performed at 100 mW and 40°C over 3200 h demonstrated excellent reliability of these SL MQW lasers (Philips). High temperature operation was enhanced by 90% HR coating on one facet. At 80°C, the threshold current was 18 mA and the external quantum efficiency was 31%. A CW output power of 10 mW was obtained at temperatures up to 110°C (Kamei, Sumitomo). Quite similar results were also obtained with 1.3 μm CBE-grown MQW lasers as have already been described above. Such high temperature performance lasers are important for data links and fiber-to-the-homes applications.

The use of MQW lasers also resulted in extremely narrow spectral linewidths of ≤ 200 kHz in DBR (Matsui, Oki) and corrugation-pitch-modulated (170 kHz) structures (Okai, Hitachi). For 1.5 μm SL QW F-P lasers, the α value is about 2, half of the unstrained QW F-P lasers (Hirayama, Toshiba).

The first demonstration of electronic wavelength tuning in single mode semiconductor laser was implemented by using the cleaved-coupled-cavity lasers (Tsang, AT&T Bell Labs). Since then the basic idea of electronic wavelength tuning using independently adjustable current injections to affect the carrier induced refractive index change was widely used also in DFB and DBR lasers. In these frequency selective lasers, tuning is accomplished around a pre-fixed wavelength. Normally, tuning occurs by continuously switching from one longitudinal mode to the next. Recently, continuous tuning over 6.1 nm using SL MQW multi-electrode DFB lasers was achieved (Wu, AT&T Bell Labs). Single mode tuning range as large as 7.2 nm with linewidth remained below 2 MHz over 6 nm of tuning was also demonstrated in three-section 1.5 µm SL MQW DFB lasers (Kuindersma, Philips). In three-section DBR lasers, 3.8 nm continuous tuning was achieved (Reid, Plessey). In short, excellent 1.3 - 1.5 µm QW lasers were obtained by both MO-VPE and CBE. Their performance in general, are improved over the bulk active lasers, though the amount of improvement is not as dramatic as in GaAs/AlGaAs QW lasers. Strained QW lasers also appear to further improve the device performance.

The advent of the Er^{3+}-doped fiber amplifier is revolutionizing the entire lightwave telecommunication and date communication technologies. An important key to the success is the laser pump. At present, there are two candidates. One is 1.48 µm InGaAsP/InP laser. The other is 0.98 µm InGaAs/AlGaAs SL QW laser. For bulk 1.48 µm pump lasers, output power was as high as 190 mW at 25°C, it was limited to 65 mW at 50°C. After 5000 h of APC aging, there was no increase in the drive current (Horikawa, Oki). For 5 QW, 1800-µm long 1.48 µm lasers, CW output powers of 250 mW (20°C) and 150 mW (70°C) were obtained. APC aging tests at 100 mW were carried out at 20°, 50°, and 70°C. All the samples tested operated stably. The average increase in the drive current for the 20°C, 100 -mW condition was 3×10^{-6}/h after 3700 h (Asano, NEC). The main advantages of 1.48-µm InGaAsP/InP lasers as pump sources are: (1) it is based on rather matured InGaAsP technologies; (2) the device reliability is believed to be less of an issue. However, because of the lower slope efficiency than 0.98 µm lasers, power input requirement will be high. Further, from the system's performance, 0.98 µm lasers offer substantial reduction in noise and hence, increased fiber span. If high power 0.98 µm lasers can be made to meet the reliability requirement, it certainly will be preferred over 1.48 µm lasers. Strained InGaAs/AlGaAs lasers have been widely investigated. CW output powers as high as 350 mW and 210 mW single longitudinal mode were obtained in SQW lasers of 500 µm long. The total power efficiency was 53%. T_0 was 120K below 80°C and 70K above 80°C. At 100 mW, 50°C, lasers appear to be stable up to 35,000 h tested (Welch, Spectra Diode Lab.). Such results are very encouraging. However, because this is a rather uncharted territory, further investigations are required, especially in view of that GaAs/AlGaAs lasers have been found to be not as reliable as InGaAsP/InP lasers.

0.8 µm AlGaAs lasers are in mass production for compact disc, laser recording, printing, and medical applications. To date, 675 nm GaInP active-layer visible lasers are also commercially available. With window lasers, pulsed output power as high as 80 mW (10 MW/cm^2) was achieved (Ueno, NEC). Shortening the lasing wavelength by introducing a quaternary AlGaInP active layer or a MQW active layer has been reported. CW operation was recently obtained at 633 mW with MQW lasers. At 77K, green emitting lasers were achieved (Valster, Philips).

Amplitude-modulated frequency-division multiplexed (AM-FDM) optical transmission systems are required for CATV networks. The 1.3-µm MQW DFB laser is an important candidate because of its possibly smaller spatial hole-burning and higher resonant relaxation frequency favored low-distortion operation. Under 42-channel modulation, at a fiber output power of 6 mW, and 0.05 modulation depth MQW DFB lasers demonstrated C/N = 55dB, CSO = -70 dB, and CTB = -70 dB. Such performance is well suitable for CATV applications (Ishino, Matsushita).

Very significant progress has been made recently in surface emitting lasers (SEL) (Iga, Tokyo Inst. of Tech.). CW operation with low threshold currents in SL InGaAs/AlGaAs MQW SEL lasers are routine. However, the series resistance still needs to be lowered. The main drawback is that the maximum output power remains low and no substantial reliability studies have been made yet. Further, SEL at longer wavelengths (1.3 - 1.5 µm) has not been very successfully implemented due to difficulty in growing high quality DBR mirrors. However, CBE can be a very suitable technique. SEL is very attractive for two-dimensional array sources. Multiple wavelength SEL arrays have been demonstrated (Chang-Hasman, Bellcore).

The advent of fiber amplifier systems require low chirp sources under modulations. As a result, external modulation becomes very attractive. Recently, very low threshold currents of 8-22 mA and high efficiences of ~ 0.2 W/A comparable to solitary DFB lasers have been achieved in monolithically integrated electro-absorption modulator/DFB lasers and operated successfully at

10 Gb/s (Ishikawa, Fujitsu).

A 1.5 μm four-channel monolithically integrated four tunable DBR lasers, four modulators, and two waveguide couplers, aiming at high-density WDM optical systems has been demonstrated to operate at 2.5 Gb/s (Yamaguchi, NEC). Such circuit permits channel spacing tuning, control, and stabilization, and low chirp operation. It can be important for dense WDM fiber amplifier systems. Another important advance in OEIC is the colliding-pulse mode-locking (CPM) lasers which generates transform-limited optical pulses at 1.5 μm wavelength with subpicosecond width and at a rate as high as 320 GHz (Wu and Chen, AT&T Bell Labs). Work also continues in the area of OEIC receivers, e.g. PIN/HBT circuits as described above (Chandrasekhar, AT&T Bell Labs; Yano, Sumitomo), and laser drivers. At present, they are aimed at high-speed operations. Perhaps such OEIC circuits should instead gain better acceptance in low-cost large-volume applications.

4. SUMMARY

In epitaxial growths, both MO-VPE and MBE have become the dominant techniques after more than two decades of development. On the horizon, it is the emerging of CBE which has been proven to be a very powerful combination of MO-VPE and MBE. In opto-electronic devices, the major activities are in the production of large-volume, low-cost short wavelength (~ 0.8 μm) AlGaAs lasers, the development of visible ($\leq$0.65 μm) AlGaInP lasers, the perfection of high-performance long-wavelength (1.3 - 1.5 μm) InGaAsP lasers, and the search for opto-electronic integrated circuits (OEIC) applications. The drive is towards distributed feedback (DFB or DBR) rather than just Fabry-Perot, towards quantum effects rather than bulk properties, towards graded-index separate confinement structure (GRINSCH) rather than double-heterostructure (DH), and towards functional integration rather than just discrete. Device performance is extending from fixed wavelength to electronically tunable lasers, from unstrained active layers to strained layers, from digital to analog modulation. System applications are expanding beyond digital transmissions into analog transmissions, beyond telecommunications into data communications, optical interconnects and switchings, and beyond optical regeneration systems into optical amplifier systems.