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VERY HIGH SIDEMODE-SUPPRESSION-RATIO DISTRIBUTED-BRAGG-REFLECTOR LASERS GROWN BY CHEMICAL BEAM EPITAXY

F. S. Choa, W. T. Tsang, R. A. Logan, R. P. Gnall, U. Koren, T. L. Koch, C. A. Burrus, M. C. Wu, Y. K. Chen, P. F. Sciortino, A. M. Sergent and P. J. Corvini

Indexing terms: Lasers, Semiconductor lasers

The fabrication and performance of InGaAs/InGaAsP multiquantum well distributed-Bragg-reflector lasers grown by chemical beam epitaxy are reported. Use of a long and weak grating, which was made on a thin and uniformly grown quaternary layer, has enabled the grating coupling constant κ to be well controlled. For most of the lasers the measured linewidths are below 10 MHz. A record high sidemode suppression ratio of 58·5 dB was obtained.

Tunable distributed-Bragg-reflector (DBR) lasers [1–3] are key elements for both a coherent and an incoherent wavelength-division-multiplexed (WDM) communication system. The laser can be used as a transmitter, a local oscillator [4], and even an active filter [5]. Recently, it has also been considered as an ideal laser source for amplitude-shift-keying (ASK) transmission [6] owing to its high sidemode suppression ratio (SMSR) compared with the unpredictable performance of that of a distributed-feedback (DFB) laser. To increase the threshold gain difference between the main mode and sidemodes of a DBR laser, we can reduce the Bragg reflection bandwidth of the laser by using a weak and long waveguide grating and increase the longitudinal mode spacing by reducing the equivalent cavity length. In either case, the key parameter that needs to be well controlled is the grating coupling constant κ which is also a very important parameter in making analogue DFB lasers for CATV applications.

Recently we have succeeded in preparing 1·3 and 1·55 μm wavelength multiquantum well (MQW) Fabry–Perot [7, 8] distributed-feedback (DFB) [9], and gain coupled DFB [10] lasers by chemical beam epitaxy (CBE) [11] and found very good crystal growth uniformity across 2 inch wafers. Taking the growth advantages of uniformity and well controlled thickness by CBE, we report the fabrication of DBR lasers with a record high SMSR of 58·5 dB.

The CBE system used is a modified Riber CBE 32 system. It can be used to grow very uniform thickness layers across the whole two inch wafer. The growth layer structure of the DBR laser is shown in Fig. 1. After the growth of a 6000 Å thick

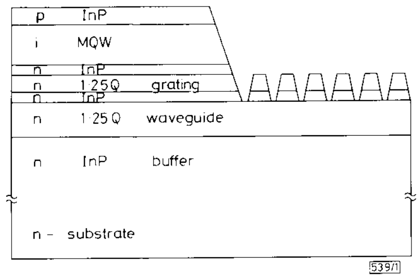

Fig. 1 *Growth layer structure of DBR laser*

InP buffer layer, a 1·25 μm wavelength InGaAsP (1·25 Q) waveguide layer with 2700 Å thickness is grown. Following growth of a thin InP etch stop layer, a 250 Å thick 1·25 Q grating layer and another InP etch stop layer are grown. The multiquantum well (MQW) gain medium is composed of six 50 Å thick InGaAs strained quantum wells and six 120 Å 1·25 Q barriers. Finally, a *p*-type InP protection layer is grown as the top layer.

The grown wafer is processed by a wet etching technique to remove the gain medium in the passive side. A holographic grating pattern is then generated and transferred to the grating layer through selective etching. Because the thickness of the grating layer is well controlled by the CBE growth time, the grating coupling constant κ is also well defined. Followed by stripe etching and semi-insulating and *p*-cap layer regrowths, the wafer is further processed for multi-electrode metallisation. The lasers are cleaved with a gain section $\sim$225 μm long and a grating section $\sim$360 μm long.

The fabricated lasers have thresholds of $\sim$20 mA. The tuning range is 21 Å. The short tuning range may partly be caused by a reduction of current tuning effect caused by the 'counter wavelength shift' by heat generation in such a long grating section. However, each laser can be easily tuned to its Bragg band centre to obtain better mode behaviour. Fig. 2

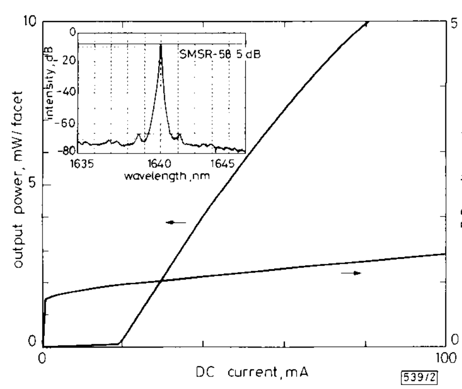

Fig. 2 *L–I and I–V curves of one of the DBR lasers*

Inset: output spectrum of laser at 87 mA bias

l_{active} = 225 μm

$l_{grating}$ = 360 μm

I_{th} = 19 mA

shows the CW biased light-current (L–I) curve and current–voltage (I–V) curve of a laser and its SMSR at a bias of 87 mA. A record high SMSR of 58·5 dB has been achieved with these lasers. For most of the lasers, 10 mW output can be easily achieved and the measured output linewidths are below 10 MHz which is attributed to the effect of the narrow Bragg bandwidth produced by the long and weak waveguide grating. The theoretically calculated κ of the laser structure employing the effective index method is $\sim 50\,cm^{-1}$. Fig. 3 shows the calculated and measured below-threshold noise spectra of a DBR laser with the gain and grating sections 225 and 360 μm

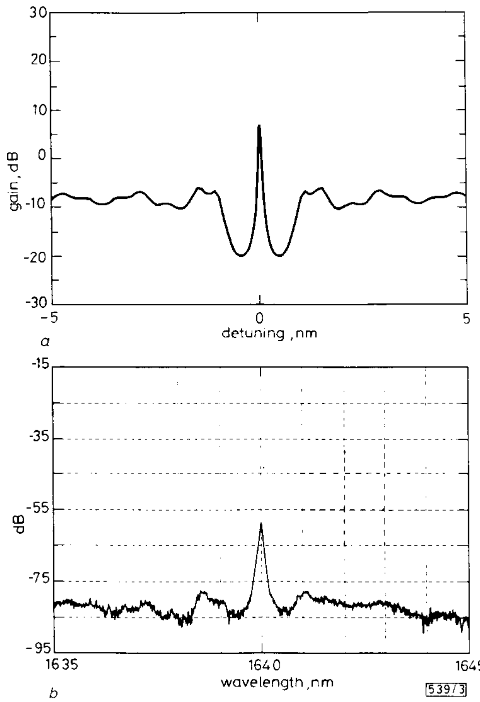

Fig. 3 *Calculated and measured output noise spectra of DBR laser with 225 μm long gain section and 360 μm long grating section*

$I_{bias} = 16\,mA$, $I_{th} = 19\,mA$, $I_{th} = 0.842$
a Calculated
b Measured

long, respectively. The waveguide loss we used in the calculation is $10\,cm^{-1}$ for the passive guide and $40\,cm^{-1}$ for the active guide. As shown in both the theoretical and measured below-threshold spectra, the two sidemodes cannot grow with increasing bias, and the Bragg band is so narrow that only one mode is allowed inside the band.

In conclusion, we have fabricated InGaAs/InGaAsP multiquantum well DBR lasers by CBE. Taking advantage of uniform thickness growth and proper design of weak and long gratings a record high SMSR of 58·5 dB was obtained.

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TRANSISTOR ACTION OF METAL ($CoSi_2$)/INSULATOR (CaF_2) HOT ELECTRON TRANSISTOR STRUCTURE

S. Muratake, M. Watanabe, T. Suemasu and M. Asada

Indexing terms: Transistors, Hot electron devices, Semiconductor devices

The first transistor action of tunnelling hot electron transistors with single-crystalline metal ($CoSi_2$)/insulator (CaF_2) has been achieved. This device consists of $CoSi_2/CaF_2$ heterojunctions grown on *n*-Si(111) substrate by ionised beam epitaxy for CaF_2 and a two step growth technique for $CoSi_2$. Transfer efficiency was more than 0·9 for hot electrons through 1·9 nm-thick $CoSi_2$ metal base layer at 77 K.

Introduction: Superlattice and ultrathin layers with the metal–insulator (M–I) combination are considered to be good candidates for ultahigh-speed electronic devices owing to the large band offset at the heterointerface in quantum effect devices, high carrier density of metal, and low dielectric constant of insulator [1–3]. In the proposed three-terminal quantum effect devices [1, 2], the potential to attain subpicosecond response has been shown theoretically.

To realise these devices, we have to study the electron transport through nanometre-thick M–I heterostructures and the conduction band of the insulator layers. This property has been extensively studied [4–6] after M–I hot electron devices were proposed [7] using the combination of an oxide tunnel barrier and a relatively thick metal layer. To our knowledge, however, no reports have been made on the transport property through a metal layer with a thickness of a few nanometres or less.

Recently, we developed an epitaxial growth technique for nanometre-thick $CoSi_2/CaF_2$ multilayered structures [8]. In this Letter, we report on the transport properties and the first transistor action of the M–I tunnelling hot electron transistor (HET) structure fabricated using this technique.

Device structure and fabrication: Single-crystalline $CoSi_2$ and CaF_2 were chosen for the metal and insulator, respectively, because they have a fluorite lattice structure and are relatively well lattice-matched to Si. The device structure and its energy-band diagram are shown in Fig. 1. The transistor is composed of a $CoSi_2$ (1·9 nm)/CaF_2 (1·9 nm)/$CoSi_2$ (1·9 nm) MIM tunnel emitter and a CaF_2 (5 nm) collector barrier on an *n*-Si(111) ($N_D \simeq 2 \times 10^{18}\,cm^{-3}$) substrate.

$CoSi_2/CaF_2$ heterostructures were grown on Si(111) by ionised beam epitaxy for CaF_2, and two step growth technique for $CoSi_2$ [8]. The agglomeration of metal on the insulator layers was suppressed and a nanometre-thick continuous film was obtained by these techniques. After the growth, the wafer was annealed at 860°C for ~ 15 min. The single-crystalline