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Midinfrared photoluminescence from IV–VI semiconductors grown on silicon

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Above room temperature continuous wave midinfrared photoluminescence has been observed from $PbSe/Pb_{1-x}Sr_xSe$ multiple quantum well structures grown by molecular beam epitaxy on (111) silicon. Emission energy from a sample with 10-nm-thick quantum wells varied from 336.1 to 343.7 meV as sample temperature was increased from 15 to 35 °C. At a heat sink temperature of 25 °C the emission energy varied from 336.8 to 339.9 meV as the current in the near-infrared diode pump laser was increased from 300 to 800 mA indicating an additional 8.2 °C of epilayer heating due to increased photon flux from the pump laser.
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Fabrication of reliable light emitting devices on silicon depends critically on the ability of the optically active material to withstand thermal stresses associated with high device operation currents. This is a fundamental problem to be solved since direct band gap semiconductor materials typically have large thermal expansion mismatches with silicon and joule heating during device operation can produce sufficient tensile or compressive stress to drive threading dislocations into device active regions. This mechanism is believed to be partly responsible for the rapid degradation of GaAs-on-Si lasers.[1] Among devices made from compound semiconductor materials grown on silicon, arguably, the most successful has been infrared detectors fabricated from IV–VI semiconductors grown by molecular beam epitaxy (MBE).[2] In spite of a more than 12% lattice parameter mismatch and a 700% thermal expansion mismatch large area focal plane arrays on silicon have been fabricated from these materials. It has also been shown that IV–VI semiconductor crystalline quality does not degrade with repeated thermal cycling.[3] Plastic deformation via complete dislocation glide through the IV–VI epilayer is believed to be responsible for crystalline quality preservation when layers are exposed to repeated cycles of tensile and compressive strain.[4] Such plasticity can make IV–VI semiconductors promising materials for fabricating reliable lasers on silicon substrates. Recently, above room temperature photoluminescence from PbSe/PbSrSe multiple quantum well (MQW) materials grown by MBE on BaF_2 substrates was reported.[5] Similar MQW structures have now been grown on silicon substrates and this article reports on the photoluminescence (PL) characterization of these materials. Experimental demonstration of light emission from IV–VI semiconductor materials grown on silicon shows that these materials may find utility in silicon-based optical interconnect technologies.

$PbSe/Pb_{1-x}Sr_xSe$ MQW structures were grown on 3 in. diameter (111)-oriented silicon substrates in an Intevac GEN II modular MBE system. Typical structures consisted of a 20-Å-thick CaF_2 layer, a 3-μm-thick $Pb_{1-x}Sr_xSe$ buffer layer, a 20–40 period MQW structure with 10-nm-thick wells (PbSe) and 50-nm-thick barriers ($Pb_{1-x}Sr_xSe$), and a 10-nm-thick PbSe capping layer to reduce strontium oxidation. The strontium content in the 3-μm-thick buffer and 50-nm-thick barrier layers was approximately 7% as determined from x-ray diffraction measurements and Vegard's law. The Sr/PbSe flux during MBE growth of the $Pb_{1-x}Sr_xSe$ layers was 3%. Detailed procedures for CaF_2 and IV–VI semiconductor growth on (111)-oriented silicon substrates are described in Ref. 6, and detailed descriptions of PbSrSe/PbSe MQW growth and characterization are published in Ref. 7. A near-IR diode laser with emission at 976 nm was used to perform the PL measurements. The experimental setup was the same as described in Ref. 5 except the diode laser was normally incident and closer to the sample surface, about 4 mm away, producing an unfocused spot size of about 2 mm in diameter. The diode laser injection current was also varied from 300 to 800 mA, and this corresponded to an approximately linear variation in pump power (density) from 160 mW (5.1 W/cm^2) to 630 mW (20 W/cm^2). A single stage thermoelectric cooling module was used to stabilize the sample temperature, which was measured with a thermistor placed adjacent to the sample, and luminescence from the MQW layer was observed through the silicon substrate.

Figure 1 shows PL spectra from a IV–VI MQW layer on silicon at temperatures of 15, 25, and 35 °C for a constant diode laser injection current of 800 mA. Multiple peaks between 300 and 420 meV are observed. These peaks, which are due to optical resonance inside the layer, are not as pro-

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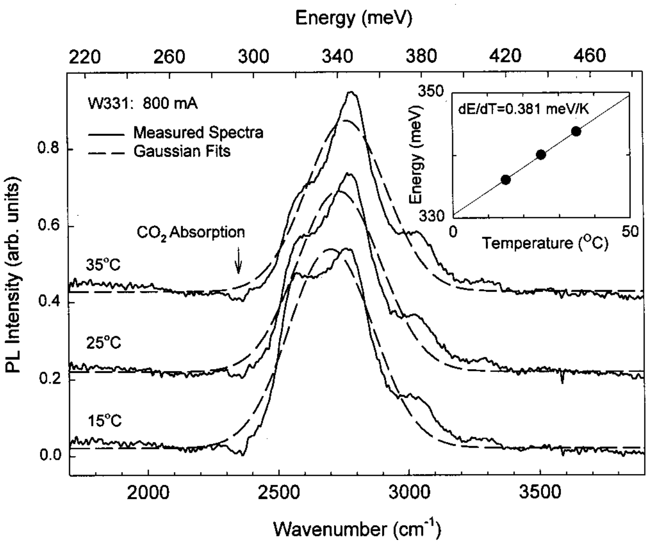

FIG. 1. PL spectra from a 20 period PbSe/PbSrSe MQW layer (10-nm-thick PbSe quantum wells) on Si(111) with a thin CaF_2 buffer layer for three different heat sink temperatures and a constant diode laser pump current of 800 mA. Gaussian fits and PL peak energy vs temperature are also shown.

nounced as those observed in the PL spectra for IV–VI MQW layers grown on BaF_2 substrates. These Fabry–Perot resonance peaks are weaker because of the much smaller refractive index contrast between the IV–VI material ($n \sim 5.4$) and silicon ($n = 3.42$) as compared to BaF_2 ($n = 1.45$). PL peak energies obtained from Gaussian fits, dashed lines in Fig. 1, vary linearly from 336.1 to 343.7 meV as the temperature is increased from 15 to 35 °C, see inset. The temperature tuning coefficient for this sample is 0.38 meV/K. It, as well as the PL energy (blueshifted by about 60 meV with respect to the room temperature band gap energy of bulk PbSe due to the quantum size effect), are similar to what were observed for 10-nm-thick IV–VI MQW structures grown on BaF_2 substrates.[5] Since PL emission has not been

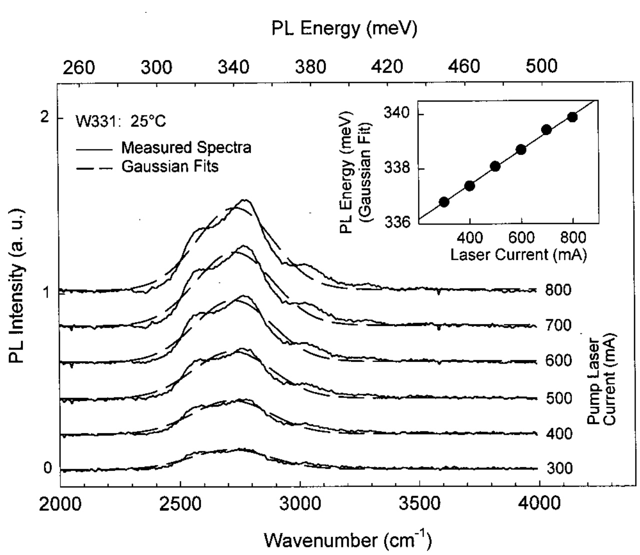

FIG. 2. PL spectra from the same MQW sample as in Fig. 1 for a constant heat sink temperature of 25 °C and six different diode laser pump currents. Gaussian fits and PL peak energies vs pump laser current are also shown.

observed from PbSe layers under these same test conditions it is concluded that the MQW structure plays an important role in enabling the observation of cw PL at room temperature.

Figure 2 shows measured PL spectra from the same sample shown in Fig. 1 at a constant temperature of 25 °C and various diode laser injection currents. Increasing pump laser power resulted in blueshifts of the PL emission. Gaussian fitted PL peak energies shifted from 336.8 to 339.9 meV as the pump laser current was increased from 300 to 800 mA. This increase in PL energy is due to localized heating of the IV–VI material associated with the higher photon flux from the near-IR laser. With a temperature tuning coefficient of 0.38 meV/K, the 3.1 meV shift corresponds to a temperature rise of 8.2° as the near-IR laser power density increases from 5.1 to 20 W/cm^2. Similar measurements have been performed with 10-nm-thick MQW layers on BaF_2 substrates, and the blueshifts are much larger, on the order of 10 meV, which corresponds to a temperature rise of 26°. Clearly, the higher thermal conductivity of the silicon substrate (1.41 W/cm K) compared to that of BaF_2 (0.12 W/cm K) improves heat dissipation from the IV–VI layer, and this reduces the amount of localized heating due to photon-phonon or excited-electron-photon scattering associated with the incident 1.27 eV near-IR photons.

Above room temperature, continuous wave PL spectra have been obtained from several different MQW layers grown on silicon substrates, including samples with 40 period MQWs, and a similar dependence of PL energy on PbSe well width (quantum size effect) is observed as with layers grown on BaF_2 substrates. The samples are quite robust, and the PL measurements are highly reproducible even after several temperature cycles and repeated near-IR laser irradiation experiments. No degradation in PL intensity has been observed either due to testing or storage in laboratory air. Strong luminescence has also been observed from MQW structures grown on silicon with ~500-nm-thick BaF_2 layers grown between the CaF_2 layer and the $Pb_{1-x}Sr_xSe$ buffer layer. Growth of such structures allows removal of the silicon growth substrate and transfer of the IV–VI layer to more thermally conductive substrates such as copper by dissolving the BaF_2 layer with water.[8,9] Ability to obtain midinfrared emission for a variety of different test conditions and from a variety of different structures grown on silicon show that these materials have promise for fabrication of reliable devices.

In summary, experimental demonstration of midinfrared emission from a IV–VI semiconductor structure grown on silicon has been described. Photoluminescence was observed at room temperature and in continuous wave mode. Peak emission energies for a 10-nm-thick PbSe MQW sample varied from 336 to 344 meV depending on sample temperature and injection current of the near-infrared diode laser pump. These measurements provide a way to quantify localized heating in an epitaxially grown layer, and results have shown the role of higher substrate thermal conductivity in enhancing heat dissipation from the optically active material. In addition to having low Auger recombination rates,[10] IV–VI MQW materials when grown on (111)-oriented substrates have properties that can enable enhanced luminescence. Potential variation in the [111] direction removes *L*-valley degeneracy because of the different longitudinal *L*-valley and oblique *L*-valley effective masses.[11] Quantum confined energy levels for the single longitudinal *L*-valley are consequently lower than those for the three-fold degenerate oblique *L*-valleys.[12] The approximate four-fold reduction in the density of the first excited states, as compared to the degenerate *L*-valley case, enables population inversion at lower generation rates. Stimulated emission from (111)-oriented IV–VI MQW materials will thus be more likely than from bulk IV–VI materials or even (100)-oriented QW materials. The physics of (111)-oriented IV–VI MQW materials are therefore favorable for laser fabrication, and continued investigation of these materials may lead to development of reliable light emitting devices on silicon for optical interconnects.

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[1] T. Egawa, Y. Hasegawa, T. Jimbo, and M. Umeno, Appl. Phys. Lett. **67**, 2995 (1995).

[2] H. Zogg, A. Fach, J. John, J. Masek, P. Müller, C. Paglino, and S. Blunier, Opt. Eng. **34**, 1964 (1995).

[3] H. Zogg, S. Blunier, A. Fach, C. Maissen, and P. Müller, Phys. Rev. B **50**, 10801 (1994).

[4] P. Müller, H. Zogg, A. Fach, J. John, C. Paglino, A. N. Tiwari, M. Krejci, and G. Kostorz, Phys. Rev. Lett. **78**, 3007 (1997).

[5] P. J. McCann, K. Namjou, and X. M. Fang, Appl. Phys. Lett. **75**, 3608 (1999).

[6] P. J. McCann, X. M. Fang, W. K. Liu, B. N. Strecker, and M. B. Santos, J. Cryst. Growth **175/176**, 1057 (1997).

[7] X. M. Fang, K. Namjou, I. Chao, P. J. McCann, N. Dai, and G. Tor, J. Vac. Sci. Technol. B **18**, 1720 (2000).

[8] H. Z. Wu, X. M. Fang, D. McAlister, R. Salas, Jr., and P. J. McCann, J. Vac. Sci. Technol. B **17**, 1263 (1999).

[9] H. Z. Wu, X. M. Fang, R. Salas, D. McAlister, and P. J. McCann, Thin Solid Films **352**, 277 (1999).

[10] P. C. Findlay *et al.*, Phys. Rev. B **58**, 12908 (1998).

[11] M. F. Khodr, P. J. McCann, and B. A. Mason, IEEE J. Quantum Electron. **94**, 1604 (1998).

[12] S. Yuan, H. Krenn, G. Springholz, G. Bauer, and M. Kriechbaum, Appl. Phys. Lett. **62**, 885 (1993).