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# Lasing properties of PbSnTe/PbTe double hetero mid-infrared laser diodes grown by temperature difference method under controlled vapor pressure liquid-phase epitaxy

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ABSTRACT

PbSnTe/PbTe double hetero-diode structures were grown by temperature difference method under controlled vapor pressure (TDM–CVP) liquid-phase epitaxy (LPE). These laser diode (LD) structures were of the PbTe (Bi)/$Pb_{1-x}Sn_xTe$/PbTe (undoped substrate) double hetero (DH) type. The peak shift of the wavelength emitted by the fabricated diodes was recorded and it was found that they successfully lased from 15 K to over 77 K (liquid nitrogen temperature) at a slightly lower threshold current density than standard LPEs fabricated via the slow-cooling method. In addition, the lasing peak wavelength was longer than spontaneous emissions. The laser spectra of diodes with varying Sn concentrations ($x$) in the active layer were observed, and their intensities were recorded as a function of the wavelength. Very sharp lasing spectra were obtained between 6.5 μm and 9.4 μm ($x$=0–0.11), clarifying that the stoichiometry control possible with TDM–CVP is suitable for fabricating optical devices. In addition, it was demonstrated that TDM–CVP is appropriate for fabricating infrared optical devices constructed from $Pb_xSn_{1-x}Te$ systems.



## 1. Introduction

Compound materials of Group IV–VI metals, including $Pb_xSn_{1-x}Te$ systems, are known as narrow and direct-gap compound semiconductors with energy gaps ($E_g$) of 0.1–0.3 eV. These materials are used in mid- to far-infrared light-emitting diodes (LEDs), laser diodes (LD), and photo diodes (PD). Because their infrared emission wavelengths (4–30 μm) coincide with the absorption peaks of many pollutant gases, these materials are potentially applicable for gas detection.

Previously, we fabricated infrared optical devices using a temperature difference method under controlled vapor pressure (TDM–CVP) liquid-phase epitaxy (LPE) [1–4]. Typically, PbTe or PbSnTe homo- or hetero-laser diode structures are fabricated via the slow cooling LPE method. Yoshikawa and colleagues reported the long continuous lasing operation of a PbTe/PbSnTe double hetero (DH) LD grown via normal cooling LPE [5]. However, the stoichiometry during crystal growth is not easily adjustable using this approach. Control is important, because defects introduced as the result of non-stoichiometry degrade the performance of semiconductor crystals.

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In our previous work, we described the properties of a Bi-doped PbTe epitaxial layer and Bi-doped homojunction PbTe laser diode, and demonstrated the effectiveness of TDM–CVP for the stoichiometric control of PbTe epitaxial crystal growth [6,7]. We also reported the lasing properties of an In-doped PbSnTe/PbTe DH LD grown via TDM–CVP and its application to basic mid-infrared spectroscopy [8].

In the present paper, we describe the fabrication and lasing properties of PbTe/$Pb_{1-x}Sn_xTe$/PbTe (undoped substrate) double hetero (DH) laser structures with varying Sn concentrations. The performance of structures grown via TDM–CVP LPE and the slow cooling LPE method are compared.

## 2. Experimental

As substrates, undoped p-type (0 0 1) oriented PbTe single crystals were grown using the Bridgman method under a controlled Te vapor pressure [9]. The hole concentration of the p-type substrates was $2\times10^{17}$ $cm^{-3}$. Each substrate surface was polished and etched to remove defects and create a mirror-like surface using a Norr etch solution (20 g KOH+45 ml $H_2O$+30 ml glycerol+20 ml ethanol) [10].

The epitaxial layer of the DH diode structure was grown via TDM–CVP LPE. The apparatus for this method is shown in Fig. 1. The first growth layer was a Tl-doped PbTe p-type buffer with a cladding layer (Tl concentration in the Pb rich melt=0.03 at%, $p=7\times10^{18}$ $cm^{-3}$). The second growth layer was the active layer, Tl-doped p-type $Pb_{1-x}Sn_xTe$.

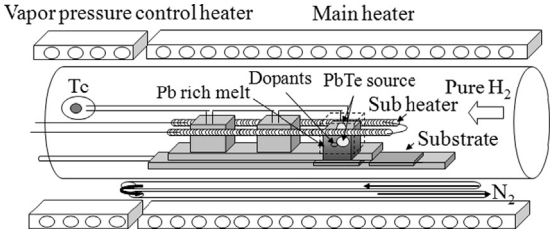


**Fig. 1.** Apparatus for the temperature-difference method under controlled vapor pressure (TDM–CVP) using liquid-phase epitaxy (LPE).

(Tl concentration in the Pb rich melt=0.01 at%, $p=2\times10^{18}$ $cm^{-3}$). In addition, by varying the Sn concentration $x$ from 0.05 to 0.11, the wavelength of the laser emission was tuned. The third growth layer was a Bi-doped (n-type PbTe cladding layer ($x_{Bi}=2\times10^{19}$ $cm^{-3}$, $n=1\times10^{17}$ $cm^{-3}$). The growth temperature was 470 °C, and the stoichiometry during crystal growth was controlled by applying a near optimum Te vapor pressure to the melts [11–13].

Ohmic contacts were formed on both sides of the p- and n-type electrodes via Pt and Au electroplating. An approximately 500 μm × 500 μm area of each of these samples was scribed using a diamond cutter to form a Fabry–Perot cavity. Diodes were then mounted on the laser stems with indium solvent.

The diode samples were placed in a cryogenic system for which the temperature was controllable between 15 K and room temperature (RT). The duty ratio of the pulse current was set between 1/164 and 1/1840, and the pulse width was varied between 10 μs and 50 μs. The emission spectra were measured using a liquid-nitrogen-cooled HgCdTe detector.

## 3. Results and discussion

Fig. 2 shows the cross section of a typical DH structure grown via TDM–CVP LPE on (1 0 0) undoped PbTe at $T_g=470$ °C. As can be seen from the figure, the interface was nearly flat. In addition, the crystals were fabricated in single layers, and the cross section was free of defects, such as cracking. The thicknesses of the Tl-doped p cladding layer, activation layer, and Bi-doped layer were approximately 2 μm, 3 μm, and 2 μm, respectively.

Fig. 3 compares the lasing and spontaneous emission spectra for a $Pb_{0.95}Sn_{0.05}Te$/PbTe DH diode. The lasing spectrum was significantly sharper than the spontaneous emission spectrum and exhibited a peak shift toward longer wavelengths. PbTe has a very high dielectric value $\varepsilon=1400$–1800 [14], the electron concentration in the Bi-doped PbTe cladding layer was $1\times10^{17}$ $cm^{-3}$, and the calculated width of the depletion layer was approximately 2 μm. Therefore, it was assumed that the depletion layer of the junction extended to the Bi-doped PbTe cladding layer,

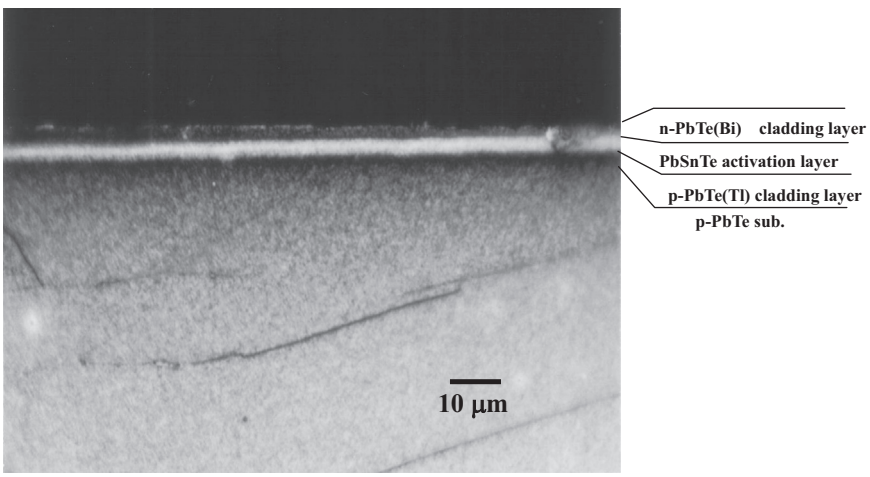


**Fig. 2.** Typical cross-sectional image of a double heterostructure grown on (0 0 1) undoped PbTe at $T_g=470$ °C.