The study of the laser characteristics based on solid solution $Pb_{1-x}Sn_xSe$ (x ≈ 0.07) emitting at spectral range of 16 µkm

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Abstract. Injection lasers were developed on the basis of the solid solution $Pb_{1-x}Sn_xSe$ for the spectral range of 16 µkm, where the rotational-vibrational absorption lines of heavy molecules are placed. For this purpose, were used, composition the solid solution $Pb_{1-x}Sn_xSe$ near the inversion point x_i= 0.12. Single crystals $Pb_{1-x}Sn_xSe$ (E_g = 0.077 eV) were grown by directional crystallization from the vapor phase.

1. Introduction
Injection lasers based on A^4B^6-type ternary compounds can be considered quite promising. Semiconductor lasers for the infrared region of the spectrum are useful for some applications (high-resolution molecular spectroscopy, high-sensitivity spectral gas analysis, medical diagnostics [1,2]. Of particular interest is the spectral region of more than 10 µkm, where the rotational-vibrational absorption lines of heavy molecules are placed.

The aim of the research is to study the threshold and the spectral characteristics of Injection lasers based on solid solution $Pb_{1-x}Sn_xSe$ for the 16 µkm spectral region.

2. Band structure $Pb_{1-x}Sn_xSe$
$Pb_{1-x}Sn_xSe$ compound has a NaCl- type crystal structure for a range of compositions $0 \le x \le 0,43$. The conduction and valence bands are the mirror image of each other, and their extremes are in the same point of k –space at L-point of Brillouin zone. Figure 1 shows schematically the band structure at 4.2 K. For $Pb_{0.85}Sn_{0.15}Se$ L_6^- and L_6^+ states are degenerate, for $Pb_{0.7}Sn_{0.3}Se$ bands are inverted. The anisotropy coefficient of $Pb_{1-x}Sn_xSe$ compounds is about 2.

Single crystals were grown from the vapor phase [3,4]. P-n junction was produced due to diffusion in the sealed vial from the lead selenide charge enriched either by chalcogen for n-type crystals or by metal for p-type crystals. Resonators were formed by cleaved planes (100).

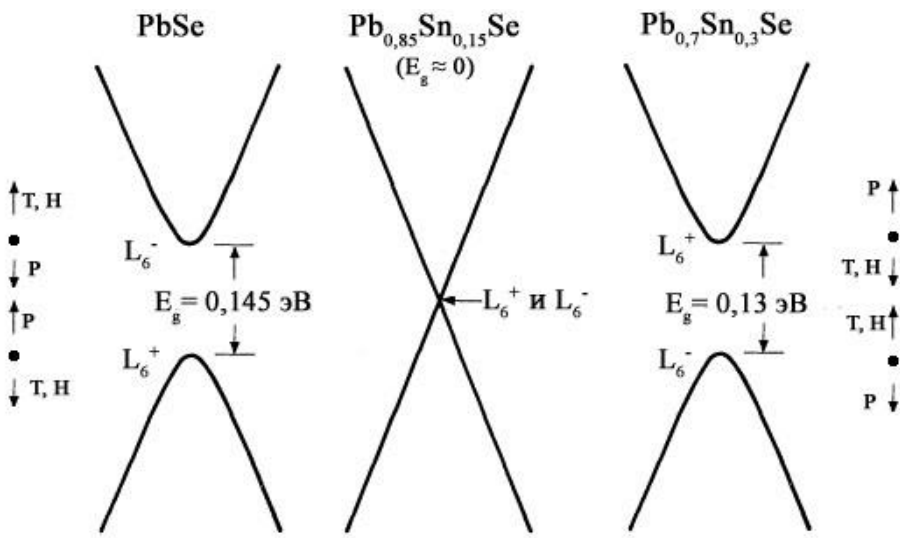

Figure 1. The inversion of the conduction band and valence band in $Pb_{1-x}Sn_xSe$ compounds as a result of the change in composition.

3. Experimental procedure

To measure the integrated intensity and emission spectra of the lasers it is necessary to use the facility shown in figure 2.It works as follows.

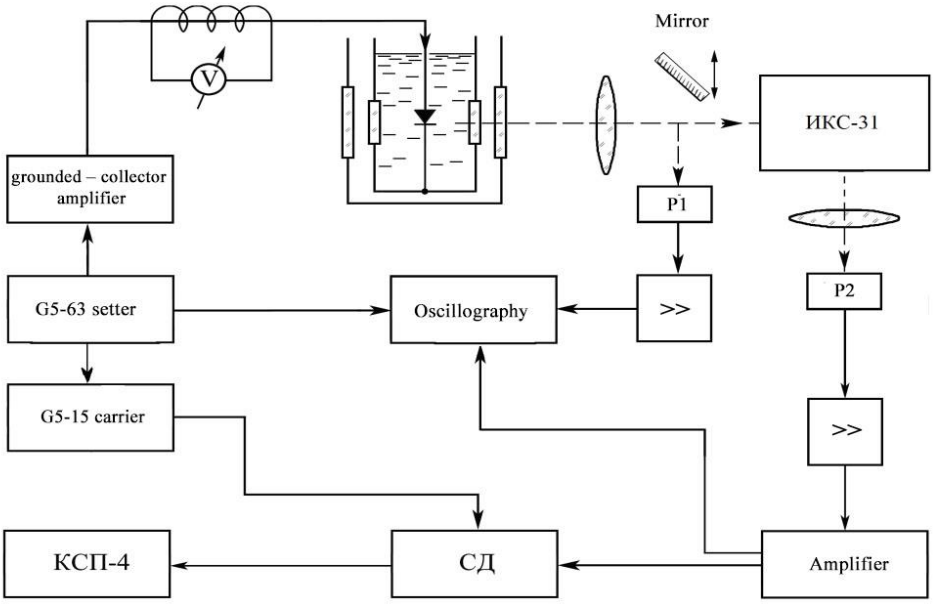

Figure 2. The setup scheme for measuring electroluminescence.

A pulse was fed to the power amplifier (grounded –collector amplifier) from G5-63 setter (oscillator), from which the current pulse was fed to the sample placed in the optical cryostat. Pulse voltmeter measured the output voltage. Diode emission was focused by a lens and then, depending on the measurements, was directed either through the mirror to the receiver R1 based on Ge: Au for measuring the integrated intensity, or to the entrance slit of the X-31-type grating monochromator (IR spectroscopy) (echelette 75 lp / mm.) for removing the emission spectrum.

At low temperature (~ 20 C) emission spectra, measurements were conducted using the vacuum-Fourier spectrometer [4] to eliminate atmospheric absorption.

4. Emission characteristics of lasers $Pb_{1-x}Sn_xSe$

We have experimentally obtained the threshold and spectral emission characteristics of $Pb_{1-x}Sn_xSe$ - based lasers (x≈ 0.07) in the 16 μkm spectral region at low temperatures (20 - 80 K).

4.1. Threshold characteristics of lasers

Threshold current was measured at liquid-helium temperature. Current-voltage characteristics (CVC) is the important characteristics of diode lasers. It determines such laser characteristics as the band gap (E_g) of the material, the threshold current, the series resistance. Since the laser diode operates at a forward bias and a large level of injection, a direct branch of the current-voltage characteristics of lasers was usually measured.

Figure 3 shows the measured values at T = 4.2 K for lasers $Pb_{1-x}Sn_xSe$ (x ≈0.07). It can be seen that the characteristics is a straight line, the slope of which is determined by the series resistance of the laser assembly, which can be calculated as R= (dU/dI) = 0.5 Ohm. Extrapolation of the straight portion to the abscissa characteristics allows defining sufficiently exactly the difference in contact potential of U_k at the p-n junction and thus determining the value E_g.

Dependence of the emission intensity on the current. At the liquid nitrogen temperature the values of the threshold current increase from 5 to 15 A. At low temperatures (T ≤ 20K) the laser threshold current ranges from 2 to 8 A. Therefore, continuous operation was impeded and all studies were carried out in a pulsed mode. Figure 4 shows the dependence of the emission intensity on the current.

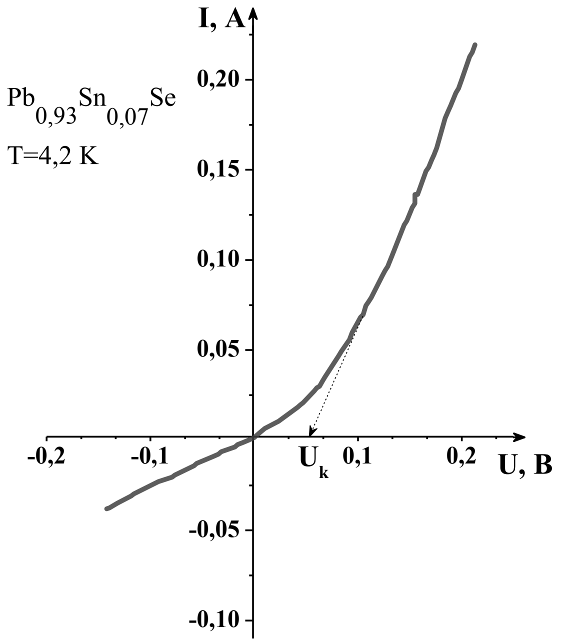

Figure 3. Current-voltage characteristics of $Pb_{1-x}Sn_xSe$ (x ≈0.07) at helium temperature.

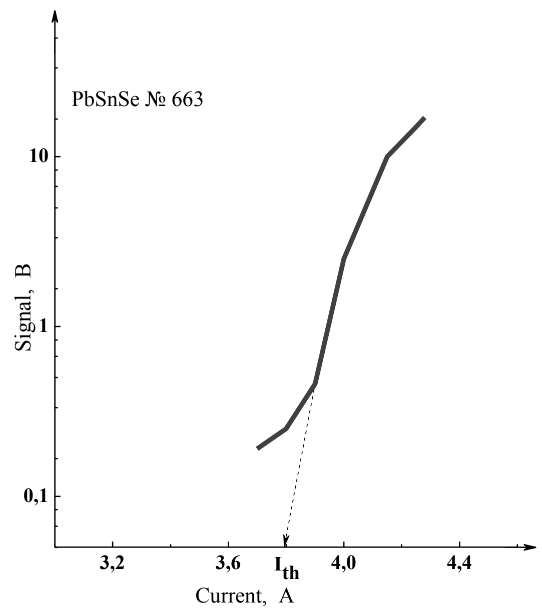

Figure 4. Dependence of the emission intensity on the current for $Pb_{1-x}Sn_xSe$ (x≈0.07) at nitrogen temperature.

This watt-ampere dependence has three sections. In the first section (the curve goes up very slightly) – the dependence close to the linear one (the more the current increases, the more the signal changes) - corresponds to spontaneous emission. The second section (the curve goes up sharply) - when a small change in the current significantly changes the signal. This section is related to stimulated emission. Subsequently, luminescence spectra showed that it was not just stimulated emission but oscillating mode (laser effect). Finally, the third section (flatter curve, again) – saturation state - when the laser is heated by the current, and its intensity decreases. The laser heating is associated with the ohmic heating of contacts and non-radiative re-combination of the active region, which also leads to heating.

4.2. Emission spectra of $Pb_{1-x}Sn_xSe$-lasers

The lasers operated at T = 19 K in pulsed mode (T = 1-5 ms) with the repetition frequency (0.17-1 kHz). When there occurred a small excess over the current threshold, the lasers worked in the single-mode oscillation. When there was a strong current excess in the emission spectrum, a series of equidistant longitudinal modes (figure 5) occurred, with transverse modes superimposed on some of them.

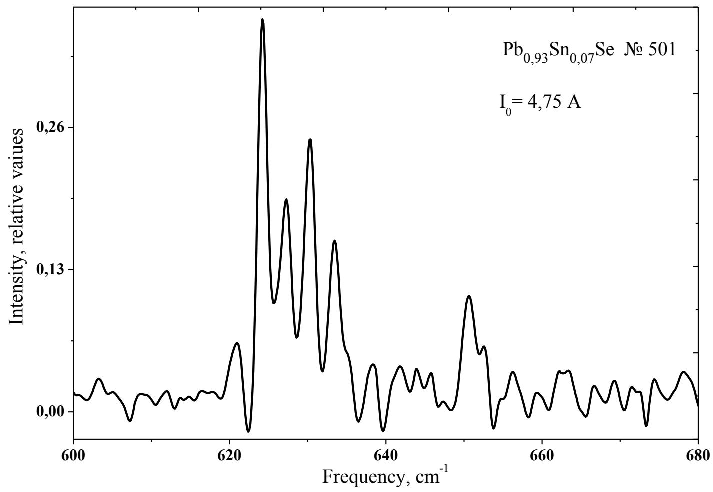

Figure 5. Emission spectrum of $Pb_{0.93}Sn_{0.07}Se$-laser № 501.

In the emission spectrum of $Pb_{0.93}Sn_{0.07}Se$-laser № 501 there are equidistant longitudinal modes. The distance between the longitudinal modes is equal, and it is about 3 cm^{-1}.

Let us consider the shift of the emission frequency of individual modes of lasers $Pb_{0.93}Sn_{0.07}Se$. Emission spectra are measured as the current changes. The rate of emission frequency tuning of 5 individual modes of lasers was calculated according to the measurements made. For this purpose, samples of $Pb_{1-x}Sn_xSe$ № 416 and № 474 with the same composition ($x \approx 0.07$) and the same emission wavelength, but with different lengths of the resonator were selected. Figure 6 shows the dependence of emission frequency on the current. Lasers emit at the wavelength of about 16 μkm. Frequency increases as the current increases. This is due to the fact that the width of the band gap E_g increases with an increase in temperature, and the sample is heated slightly with an increase in the impressed current.

Figure 7 shows the spectra of laser emission depending on the current injection at 19 K. With the current increasing, the stimulated emission of the laser increases through forming different generation modes. At larger currents a greater amount of modes in the emission spectrum is separated. Most lasers operate in the multimode regime. The main reasons for multimode nature are as follows. Each mode is unique in its spatial heterogeneity and stationary localization in the active medium. Sections of the active laser medium, located in the wave nodes, do not almost give off their energy to the lasing mode. The level of inverse population of such sections increases as pumping increases. Therefore, there are favorable conditions for generating other types of waves whose antinodes and nodes are located differently in space.

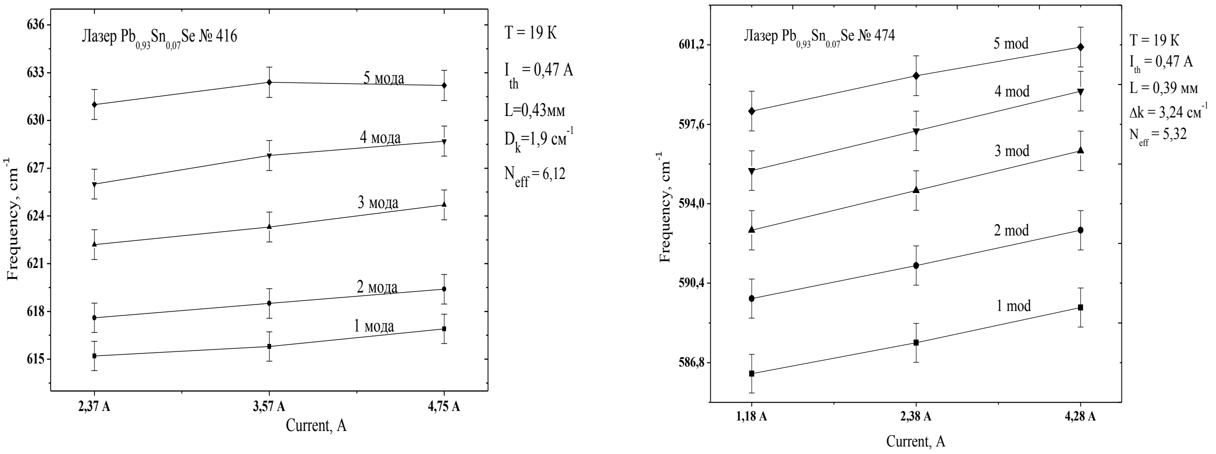

Figure 6. The shift of the emission frequency of individual modes of lasers $Pb_{0.93}Sn_{0.07}Se$ № 416 (left) and №474 (right).

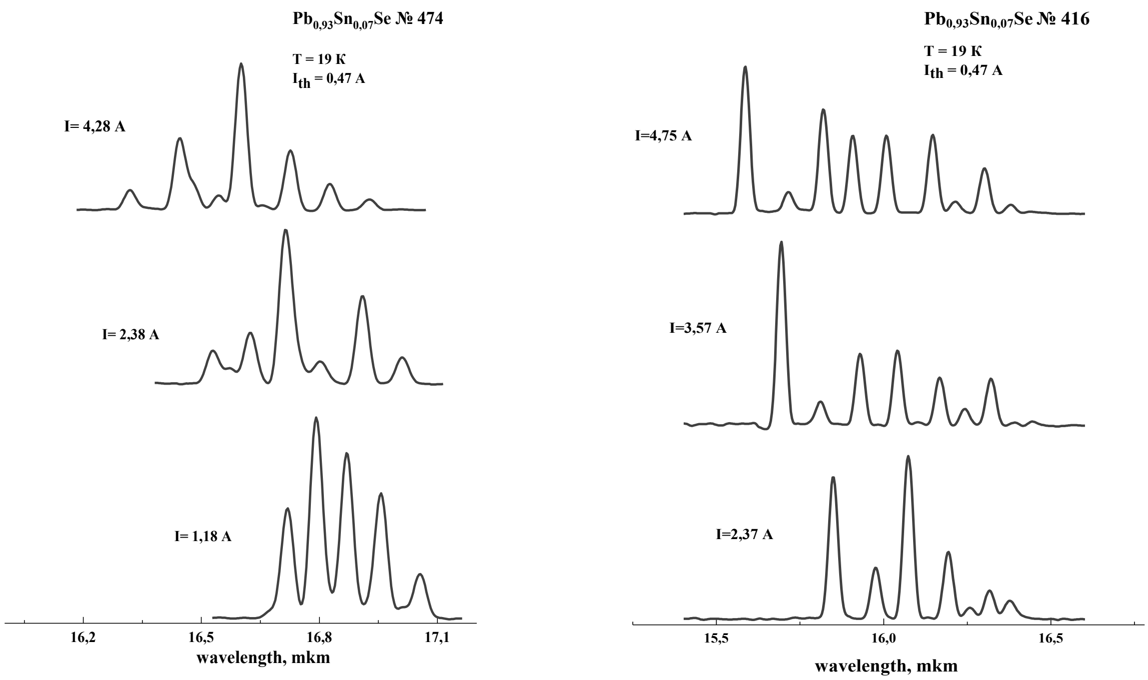

Figure 7. Emission spectra of lasers $Pb_{0.93}Sn_{0.07}Se$ № 416 (left) and № 474 (right).

According to our measurements, the effective refractive index was calculated by the formula:

$$\Delta k = \frac{1}{2LN^*}$$

As seen from the calculation, for a diode laser Pb0.93Sn0.07Se № 501 with a series of equidistant modes, at the measured inter-mode distance Δk = 3.2 cm^{-1} and resonator length L = 0.25 mm the effective refractive index is N^* = 6.25 for a given composition of the solid solution $x \approx 0.07$. With account for the data from [1,2], the dependence of the effective refractive index on the composition (figure 8) $N^* = 5.1 + 17x$ was obtained.

Table1. Effective refractive index of the active medium

x	Laser number	L, mm	T = 19 K				
			I_{th}, A	Δk, cm^{-1}	N*	Tuning	
						10^{-3}, cm^{-1}/ mA	MHz / mA
0.07	416	0.43	0.47	1.9	6.1	1.4	40
0.07	474	0.29	0.47	3.24	5,32	1.04	30
0.07	501	0.25	2.38	3.2	6.25		

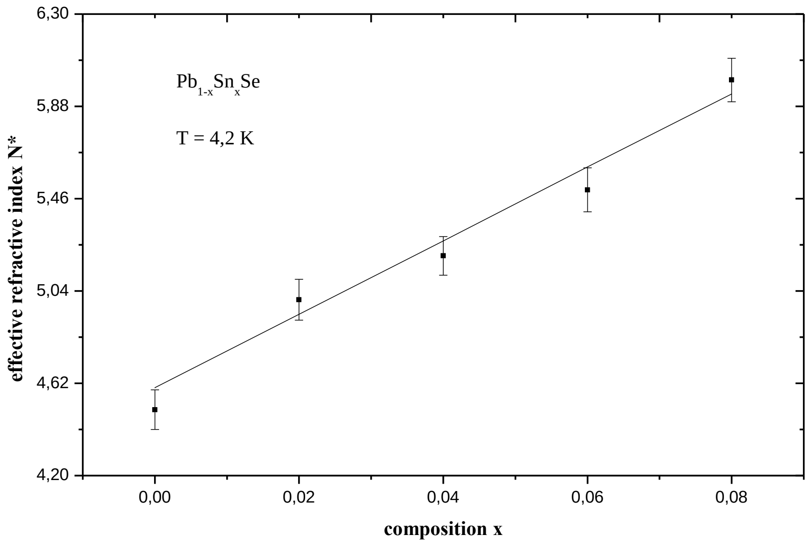

Figure 8. Dependence of the effective refractive index on composition.

5. Conclusion

1. Diode lasers for the spectral region of about 16 μkm have been developed on the basis of the solid solution $Pb_{1-x}Sn_xSe$.
2. Contact potential difference and resistance have been measured by means of the current-voltage characteristics.
3. The threshold current density of diode lasers has been defined from watt-ampere characteristics over the extrapolation of the steep section to the horizontal axis.
4. The working temperature of the laser in the pulse mode was in the range from 4.2 to 77.4 K. Threshold currents varied from 0.5 to 2 A, respectively.
5. The effective refractive index has been determined from the emission spectra, depending on the composition and tuning rate of individual modes with the current.

Acknowledgments
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