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ANALYSIS OF MATERIALS OF HEAT SINKS FOR INJECTION LASERS WITH INTERNAL ACOUSTIC MODULATION OF RADIATION

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A theoretical analysis of materials that are potentially suitable for fabrication of heat sinks of injection lasers with internal acoustic modulation of radiation is carried out. The conditions under which the heat sink can also function as a sound duct and a thermocompensator in brazing are determined.

Acoustic oscillations (AO) are introduced into devices for internal acoustic modulation of radiation of injection lasers (IL) either by forming a transducer of AO directly on the surface of the laser crystal (LC) [1, 2] or via a sound duct [3] using an acoustic matching contact [4]. The latter means of introducing AO has the advantage over the former that makes it possible to employ commercially utilized and dependable designs of LC and to obtain higher intensities of AO as a result of better conditions of heat removal. In this case the following requirements are imposed on the material of the heat sink: height thermal conductivity that provides efficient oscillation of the laser diode, low absorption of AO at the frequencies of modulation (above 100 MHz), a value of the thermal expansion coefficient close to that of the semiconductor layer of the LC connected to the heat sink/sound duct.

It is difficult to meet simultaneously the requirements of an extremely low absorption coefficient of acoustic oscillations Γ/f^2 and a reasonably high heat conduction coefficient κ (e.g., close to the value $\kappa = 400$ W/(m·K) for Cu, which is the basic material of heat sinks of IL, or even higher) for the material since they are contradictory in their physical essence: within the Akhiezer approximation these two quantities are directly proportional in relaxing media [5], and therefore a material with an extremely low Γ will not possess a high value of κ, and a material with a high value of κ will not possess a low value of Γ. This leads to the conclusion that a solution to the problem posed is possible only on the basis of a combined approach to the choice of the desired material. The search for materials for fabrication of a sound duct is also hindered by the absence of both experimental data simultaneously on Γ and κ for a variety of crystals and a simple and dependable general method for calculating the quantity Γ. This difficulty can be partially overcome by estimating the value of Γ/f^2 or κ if the experimental value of one of these parameters is known using the equation obtained in [6]:

$$\Gamma/f^2 = 304\,(\bar{\gamma}/\bar{\gamma}_T)^2\ [(\kappa_\theta/\kappa'_\theta)\,(300/\theta^2)\,V_0^{-1/3}], \tag{1}$$

where $\bar{\gamma}$ is the averaged value of the Gruneisen parameter, equal to 0.6–1.2 for the majority of cubic crystals; $\bar{\gamma}_T = 2$ is the averaged value of the Gruneisen parameter obtained from measurements of thermal conductivity; θ is the Debye temperature; V_0 is the mean volume per atom of the elementary cell of the crystal lattice; κ_θ is the thermal conductivity coefficient measured at the Debye temperature; $\kappa'_\theta = 5.72\cdot10^{-8}(M\theta^2 V_0^{1/3}\bar{\gamma}^{-2})$ is the calculated value of the thermal conductivity coefficient at the Debye temperature; M is the mean atomic weight of the substance.

Calculated and reference data [7-9] for materials satisfying each of the combined requirements to one extent or another are shown in Table 1.

For the subsequent substantiation of the choice of the material of the heat sink/sound duct we define minimum values of its κ at which the cw mode of IL oscillation is maintained. The calculations will be carried out

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TABLE 1. Some Physical Properties of Materials of Sound Ducts and Heat Sinks

Material	Orientation	κ, W/(m·K)	$\alpha \cdot 10^{-6}$, K^{-1}	Γ/f^2, dB/(cm·GHz^2)	Note
		300 K			
C(IIa)	[100]	$2 \cdot 10^3$	0.9...1.3($\perp$C)	1.5	
6H–SiC	[0001]	400...500	2.3	0.475	
AlN	[0001]	320	5.27($\perp$C)	2.1...8.6*	
BN(kII)		$1.3 \cdot 10^3$	3.56	1.3...5.3*	300...700 K
BeO	[0001]	152...209	7.0	1.09	
GaAs	[110]	45	5.6	30	
Si	[110]	150...180	2.33	6.3±0.4	
B	[001]	26	8.3	0.1	300...700 K
YAG		13	6.8	0.2...0.3	300...400 K
MgO	[110]	58	11	3.3	
α-Al_2O_3	[100]	27...47	6.66	0.18	
$LiTaO_3$	[100]	2.93	4.1	$(4...6) \cdot 10^{-2}$	
Cu		400	16.5	$5.7 \cdot 10^2$	
Tl_3TaS_4	[100]	$1.46 \cdot 10^3$	18	$7.6 \cdot 10^{2}$*	

* Data calculated using formula (1).

for a band heterolaser based on an AlGaAs double-sided heterostructure (DHS) with optimum parameters of the layers [10], which provide the characteristic values of the thermal resistance of the LC itself $R_{cr} \approx$ 80 and 20 K/W upon fastening it to the heat sink by the substrate or by the epitaxial surface, respectively. Let the value of the power radiated from one of the mirrors be 1 or 30 mW. For a band DHS laser with the width and the height of the waveguide equal to 15 and 0.2 mm, respectively, the latter power is close to the value of the critical optical flux density 10^6 W/cm^2 [11]. We take the maximum allowable value of overheating of the active medium to be 50 K. Within the chosen range of values of the optical power for the given type of devices, depending on the type of assembly this value of overheating corresponds to 2–10-fold excess overheating and, correspondingly, a 2–10-fold decrease in the service life for the same devices but with optimum heat removal conditions [12]. The expression for the optical power radiated from one of the mirrors of the cavity in the cw mode is as follows [13]:

$$S = 0.5\,\Phi\,\eta(T)\,[I - I_t(T)],$$

where $\eta(T) = \eta_0(1 - \gamma\Delta T)$; $I_t(T) = I_0(1 + A\Delta T)$; $\Phi \sim eV$ is the energy of the radiated flux; $V \approx 1.3$ V is the voltage on the p-n junction; $I_t(T)$ and $\eta(T)$ are the threshold current and the external differential quantum efficiency at the temperature T of the surrounding medium, measured in a pulsed regime without overheating; I_0 and η_0 are the same quantities but measured at room temperature; I is the working current; A and γ are coefficients determined by the height of the heterobarrier, equal to 0.012 and 0.008, repectively (which corresponds to the compositions of an $Al_{0.3}Ga_{0.7}As$ wide-band emitter and of the active zone of $Al_{0.05}Ga_{0.95}As$).

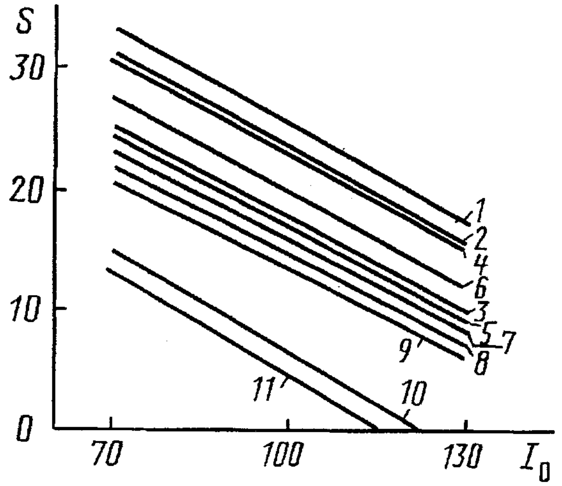
Taking the values $\eta_0 = 50\%$, $I_0 = 50$, 100, and 150 mA we calculate the values of the working currents I corresponding to the values $\Delta T = 50$ K, $P = 1$ and 30 mW. After this we determine the heat resistance of the device from the equations

$$R_T = R_{cr} + R_{T0}, \quad \Delta T = R_T I_T V, \quad I_T = I_t(T) + [I - I_t(T)]\,[1 - \eta(T)],$$

TABLE 2. Calculated Values of the Minimum κ of the Material of a Heat Sink for the cw Mode of an Injection Laser

I, mA	κ, W/(m·K)			
	$S = 30$ mW		$S = 1$ mW	
	A	B	A	B
50	9.69	6.76	7.2	4.7
100	16.55	14.24	13.8	10.85
150	24.10	27.89	21.1	21.47

Note. A, fastening to the heat sink by the substrate; B, by the epitaxial surface.



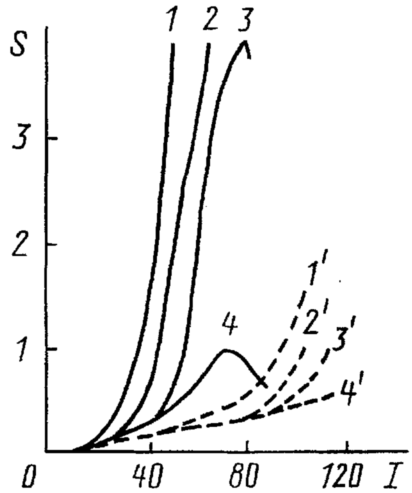


Fig. 1. Dependence of the radiated power of an $Al_{0.3}Ga_{0.7}As$ injection DHS band laser ($\omega = 1.5\ \mu m$, $L = 250\ \mu m$, $\eta_0 = 40\%$) in the cw mode at 300 K on the value of the threshold current in the pulsed regime for the constant value of the working current $I = 200$ mA. Fastening of the laser crystals by the epitaxial surface (1, 2, 4, 6, 8, 10) and by the substrate (3, 5, 7, 9, 11) to heat sinks fabricated from the following materials: 1) C(IIa); 2, 3) Cu; 4, 5) BeO; 6, 7) MgO; 8, 9) Al_2O_3; 10, 11) YAG. S, mW; I_0, mA.

Fig. 2. Power-current characteristics of AlGaAs mesaband DHS lasers at 296 K in the pulsed oscillation mode on a massive heat sink of YAG. Duration of the current pulse: 1, 1') 100 nsec; 2, 2') 500 nsec; 3, 3') 1 μsec; 4, 4') 3 μsec; period of pulses 5 μsec. The crystals were brazed with indium to the heat sink by the substrate. 1-4 and 1'-4' are data for two spesimens. I, mA.

where R_{T0} is the heat resistance of the heat sink; I_T is the current going into heating up the active zone.

The corresponding value of the heat conduction can be found from the expression for calculating the heat resistance of a semi-infinite heat sink [10]:

$$\pi L\kappa R_{T0} = \sin h^{-1} a + a \sin h^{-1} (1/a) - 1/3\ [1/a\,(1 + a^2)^{3/2} - 1/a - a^2],$$

where L is the length of the active zone; H is the effective width of the heat flux at the crystal – heat sink boundary, and $a = L/H$. Results of the calculation are presented in Table 2.

The values of κ obtained are somewhat underestimated since heating of the active zone due to Joule heat, which gives an additional increase in the temperature by several degrees [10, 13, 14], was not taken into account in the calculations.

The data of Tables 1 and 2 make it possible to choose materials that are potentially suitable for use as heat sinks/sound ducts and to make comparative estimates of the power parameters of the fabricated devices. Figure

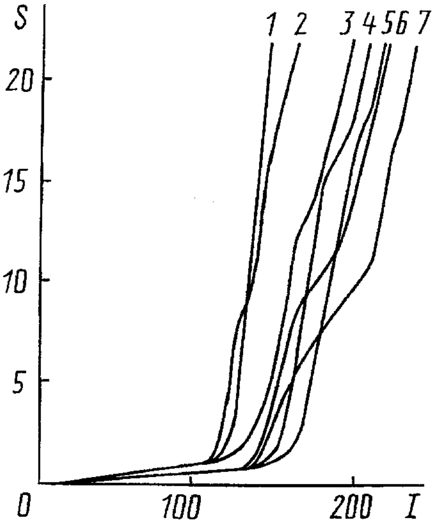


Fig. 3. Power-current characteristics of AlGaAs mesaband DHS lasers in the cw oscillation mode at 296 K. The crystals were mounted on SiC chips with the thickness 200 (1, 3) and 500 μm (2) and Si chips 200 μm thick (4–7). The crystals were brazed with indium to the chips by the epitaxial surface.

1 presents calculated dependences $S = f(I_0)$ for $Al_{0.3}Ga_{0.7}As$ band DHS lasers with the optimum geometry of the layers, $L = 250$ μm, $\omega = 15$ μm, $\eta = 40\%$, heat sinks for which were fabricated from six materials from Table 1. (The values of κ for Si, BeO, and α-Al_2O_3 were taken to be 150, 200, and 27.6 W/(m·K), respectively.) The shape of the heat sinks was taken to be semi-infinite. The calculations were carried out for a constant working current I = 200 mA for three values of I_0: 70, 100, and 130 mA.

The results obtained show that a change from a copper heat sink to a single-crystal one fabricated from BeO, all other factors being the same, leads to an insignificant decrease in the lasing power, equal to 0.4–1.0%, although κ decreases twofold. This is a result of the fact that the third layer of p-$Al_{0.3}Ga_{0.7}As$, which has $\kappa = 12$ W/(m·K) [10], determines the value of the heat resistance in this case. The same fact also explains the relatively small gain in S (14.6% compared to the copper heat sink) in the case of a diamond heat sink despite a fivefold increase in κ. The power parameters of devices with heat sinks made of AlN single crystals ($\kappa = 320$ W/(m·K)) are practically the same as those for the devices with the copper heat sink but they can be improved somewhat (by not more than several percent) with respect to the latter when high-quality 6H-SiC single crystals ($\kappa = 500$ W/(m·K)) are used. The oscillation conditions of the laser are impaired more substantially by the use of MgO, α-Al_2O_3, and YAG single-crystals. In the latter case oscillation in the cw mode becomes impossible if the value of the pulsed threshold current exceeds 120 mA at room temperature.

As an illustration of the results obtained, Figs. 2 and 3 present experimentally obtained power-current characteristics of AlGaAs mesaband DHS injection lasers assembled on single-crystal heat sinks of two types: massive ones fabricated from YAG (Fig. 2) and ones fabricated from the KDB-003 (111) Si: (Fig. 3, curves 4-7) and (0001) 6H-SiC (Fig. 3, curves 1-3) in the form of 2×2-mm chips of thickness 0.2 and 0.5 mm. The surfaces to be joined were metallized with Ni with a sublayer of Cr of total thickness 0.2-0.6 μm and solder (indium or POS-61 (Sn ~ 60%, Pb ~40%)) 3–10 μm thick. LC were brazed to YAG from the substrate side with indium. One surface of the chips was brazed with indium (3 μm) to the LC on the side of the active zone, whereas the reverse side was brazed to a copper crystal-holder with POS-61 solder.

The third requirement whose fulfillment is desirable when choosing a material for a heat sink/sound duct is connected, as was stated above, with the value of the thermal expansion coefficient. Matching the heat sink to the LC with respect to this parameter makes it possible to employ brazing solders, which is favorable for the dependability of the laser. Let us calculate the stresses σ that can arise in an LC with a contact layer of GaAs after mounting it on various single-crystal heat sinks using Sn and an Au–Ge eutectic (melting temperatures of 505 and 636 K, respectively) from the formula [15]

TABLE 3. Calculated Values of Stresses Introduced in Mounting a Laser Crystal on Massive Single-Crystal Heat Sink/Sound Ducts

Single-crystal	$\alpha \cdot 10^{-6}$, K^{-1} (300...505 K)	$\sigma \cdot 10^7$, Pa	$\alpha \cdot 10^{-6}$, K^{-1} (300...636 K)	$\sigma \cdot 10^7$, Pa
	Sn solder		Au−Ge solder	
GaAs	6.3	–	6.5	–
C(IIa)	2.2	−13.18	2.7	−20
Si	2.9	−10.93	3.2	−17.4
6H−SiC	2.82	−11.0	3.18	17.7
BeO	8.0	5.47	8.2	8.97
MgO	11.6	17	12.4	31.1
α-Al_2O_3	6.44	0.45	6.96	2.4
YAG	6.5...7.7	0.32...1.1	7.1...7.7	2.1...3.7

$$\sigma = \frac{E}{1 - \nu} (\alpha_1 - \alpha_2) \Delta T ,$$

where E and ν are Young's modulus and the Poisson coefficient for GaAs in the <110> direction, equal respectively to $1.2 \cdot 10^{11}$ Pa and 0.253 [16]; ΔT is the difference between room temperature and the melting temperature of the solder; α_1 and α_2 are the thermal expansion coefficients of the material of the sound duct and the LC, respectively.

The results of the calculation (Table 3) show that mounting an LC using an Au−Ge eutectic can be done only in the case of α-Al_2O_3 and YAG single-crystals, since in this case the obtained values of σ do not exceed the limit ($\approx 3-5 \cdot 10^7$ Pa) beginning at which acceleration of degradation phenomena was observed in an IL [17]. Analogous calculations for AlN are difficult due to lack of data on its thermal expansion coefficient within a wide temperature range. However, based on the fact that at room temperature the thermal expansion coefficient of AlN (in the direction $_\perp$C) is closer to that of GaAs (the difference is 5.89%) than in the case of α−Al_2O_3 and YAG crystals, one can assume that the stresses that can appear in the course of mounting a laser crystal on AlN using an Au−Ge eutectic will be less than $2 \cdot 10^7$ Pa.

Based on the analysis carried out, the following conclusions and recommendations can be made. Single-crystal 6H-SiC is a material that is optimum as a heat sink/sound duct of devices for internal acoustic modulation of IL radiation; it meets the combined requirements of fabrication of a durable and efficient device for the high-frequency range of modulating signals. In addition to a very favorable combination of properties (κ, thermal expansion coefficient, Γ/f^2), commercial availability of this material is a substantial argument in favor of its use.

Use of AlN, which possesses the best matching with respect to the thermal expansion coefficient, presently does not seem to be promising since the crystals are not produced commercially and reliable experimental results on attenuation of acoustic vibrations in this material are not available.

Use of C(IIa) or BN(kII) as heat sink/sound ducts is recommended for devices for which the limiting power of the emitted radiation is the most important parameter. It should be noted, however, that the production of these materials in the form of single-crystals of sufficient dimensions (e.g., 1×1×0.2 mm) has not been undertaken, although it may turn out to be less expensive than the production of diamonds.

Use of heat sinks/sound ducts of (111) or (110) Si as an inexpensive material widely used in microelectronics can be promising for fabrication of low-power devices (the value of the power of continuous oscillation for which is of the order of several mW) for acoustic modulation in the case where the modulation frequencies do not exceed 2.5 GHz.

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