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Improving the efficiency of high-power diode lasers using diamond heat sinks

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***Abstract*. Using multifunctional ion beam and magnetron sputtering systems, we have developed chemical and vacuum techniques for producing metallic coatings firmly adherent to various surfaces, with application to copper and diamond heat sinks for diode lasers. Conditions have been optimised for mounting diode lasers and bars using the proposed metallisation processes, and significant improvements in the output parameters of the devices have been achieved. The power output of cw laser diodes on diamond heat sinks increases by up to a factor of 2, the linear (working) portion of their power-current characteristic becomes markedly broader, and their slope efficiency increases by a factor of 1.5 – 2 relative to that of lasers on copper heat spreaders. The use of diamond heat sinks extends the drive current range of pulsed diode bars by a factor of 2 – 3 and enables them to operate at more than one order of magnitude longer pump pulse durations (up to milliseconds) when the pulse repetition rate is at least 10 Hz.**

Keywords: *high-power diode lasers, thermal processes, diamond heat sink substrates, high-adhesion metallisation, laser fabrication technology, output characteristics.*

1. Introduction

Laser diodes (LDs) and diode bars having output powers from a few to tens and hundreds of watts require effective heat removal from the active region of the semiconductor heterostructure. It was shown as early as the late 1960s [1] that diamond crystals can be employed as effective heat sink bases for semiconductor lasers. The thermal conductivity of diamond is one of its most remarkable properties. It exceeds by severalfold the thermal conductivity of all other solid materials: metals, semiconductors and dielectrics [2], including copper, which is used most frequently to remove heat in electronics. Diamond is also applied as a highly effective heat sink material in other semiconductor devices, such as avalanche and Gunn diodes [1, 3, 4]. The use of diamond in commercial applications is however limited by its relatively high cost and a number of technical problems.

In this work, with the aim of solving these problems we analyse the possibility of using synthetic and natural, single-crystal and polycrystalline diamond and its thermal performance. The advantages of diamond as a heat sink material manifest themselves only when its thermal resistance R_{th} exceeds that of all other components of the device [1]. As will be shown below, this can be achieved by using a new approach to the metallisation of diamond heat sink bases (DHBs), which ensures sufficiently good and uniform adhesion of the metallic coating, and by developing an appropriate mounting process for diode structures.

Superhard materials, including diamond, are composed of atoms in stable electronic configurations and are non-reactive with most metals and solders. Adequate adhesion to diamond might be offered by metals that have high chemical affinity for carbon, preferably those that form carbides possessing metallic bonding and metallic properties (chromium, titanium, niobium, zirconium, tantalum, molybdenum and tungsten). The development of a process for applying high-adhesion metallic coatings to diamond is an important practical issue, which is far from being resolved.

According to previous data [5, 6], the thermal performance of a DHB depends not only on the good adhesion of its metallic coating but also on the electrical conductance of the coating, which should be high enough that Joule heating of the base is insignificant. These conditions are however difficult to meet simultaneously because the desired adhesion strength can be achieved at a coating thickness $d \leqslant 0.1$ μm, whereas good electrical conductance is ensured by $d > 0.1$ μm. Moreover, an important requirement is uniform adhesion to the main surfaces of the base: mounting surface, backside and lateral sides (which ensure electrical connection between the first two surfaces at the minimum resistivity of the metallic coating). The results of our early experiments indicate that chemical deposition of nickel ensures the best adhesion of the DHB's coating compared to other deposition processes but fails to ensure the desired uniformity. This was interpreted in terms of the difference in physical properties between the surfaces in question and the growth features of the crystals used. Subsequently, the deposition process was modified by introducing additional surface treatment steps (cleaning

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and activation) and successfully applied to cubic boron nitride (c-BN), a diamond analogue attractive for our purposes. Issues pertaining to the application of c-BN and DHBs and the advantages and drawbacks of the two structures will be addressed separately.

In this paper, we examine the possibility and fundamental aspects of the metallisation of heat sinks from natural and synthetic (single-crystal and polycrystalline) diamond via deposition of three-layer (Ti – Ni – Ni, Ti – Al – Ni and Cr – Ni – Ni) coatings by different techniques. Ti – Ni – Ni was used as a model system to establish conditions for the preparation of uniform, high-adhesion metallic coatings on a diamond base with the required low resistivity relative to all exposed surfaces. Similar results were obtained in the other systems. DHBs were metallised as follows: First, a Ti underlayer was grown on diamond by low-pressure plasma deposition from a charge-separated plasma, followed by chemical deposition of a Ni layer from an electrolyte solution. Next, Ni was deposited by ion beam (or magnetron) sputtering until the coating had the desired thickness. These techniques were used to develop a mounting process for diode lasers and bars. The best results were obtained when metallic coatings on the components of laser structures were produced by ion beam sputtering.

2. Growth of metallic coatings on diamond heat sinks and laser mounting process

The vacuum processes developed by us for producing metallic coatings firmly adherent to various surfaces take advantage of multifunctional ion beam and magnetron sputtering systems and employ interstitial alloys with high affinity for carbon as adhesive layers [5]. In particular, Ti/Ni films were grown by ion beam sputtering at a pressure of 7.8×10^{-2} Pa in a Leybold-Heraeus Z-400 system with oil-free pumping. The diamond base was preheated to 200 – 350 °C. Metallisation was performed using a purpose-designed sputtering system, which allowed surface treatment with an about 1 keV argon ion beam prior to film growth. This treatment was intended to remove the contamination and low-cohesion, disturbed layer from the diamond surface and ensured adequate adhesion of the metallic coating, at the bond energy level. The thickness of the titanium films was ~ 20 nm (deposition rate, 0.2 – 0.25 nm s^{-1}) and that of the nickel films was about 300 nm (deposition rate, 0.35 nm s^{-1}).

According to the proposed mounting process, the metallisation and surface precleaning of DHBs are performed as a single, continuous cycle, followed by nickel layer growth to a thickness of 0.2 – 0.3 μm (contact layer) and thermal annealing at 400 – 450 °C for 30 – 40 min under vacuum or not. Next, the DHB is joined to a massive metallic heat sink by the high-temperature composite solder POS-61 in a reducing atmosphere (dry purified H_2). The composite solder is applied to the backside of the diamond heat sink by resistive thermal evaporation or another technique (layer thickness, 4 – 6 μm). The same technique is used to grow an indium layer 3 – 5 μm thick on the mounting surface of the heat sink. Next, the active element (a single LD or LD bar of length L) is positioned in the working region of the mounting surface with the desired accuracy using a microscope.

The resultant structure is placed in a purpose-designed holder, which is then loaded into the quartz chamber (reactor) of a furnace. Soldering is performed under a reducing atmosphere in dynamic mode (heating/cooling time, 3 – 5 min) at a temperature $T_{\max} \geqslant T_{\text{liq}} + (50-70)$ °C, where T_{liq} is the liquidus temperature of the material ($T_{\text{liq}} \approx 190$ °C for POS-61 and 156.8 °C for indium). The holder design enables soldering both under a predetermined mechanical load and with no load. The main mounting steps are separated by as short a time interval as possible (within 1 h), and the required environment is maintained. The last step of the mounting process is the attachment of wire leads to the heterostructure (by ultrasonic welding). If necessary, the system is enclosed in a standard package secured in a radiator.

After the DHB metallisation, the quality of the coating (adhesion and uniformity) was evaluated both visually and by optical microscopy, and its electrical conductivity and thermal parameters (thermal resistance and thermal conductivity) were measured. The module was disassembled, and the adhesion strength was evaluated using pull-off adhesion tests (with a bench-top dynamometer) or scratch tests (with MIM-7 and MII-4 microscopes).

3. Effect of mounting process conditions on the main characteristics of laser diode structures

DHBs for diode lasers were fabricated from MSTM Almazot synthetic diamond single crystals grown by a temperature gradient process from a carbon solution in a molten metal at high pressures and temperatures. The crystals were cut out along one of the square faces of a truncated octahedron and were $\sim 1.5 \times 1.5 \times 0.3$ mm in dimensions. After polishing, the surface roughness of the DHBs was 2.8 – 12.8 nm. In some instances, we used natural diamond specimens and polycrystalline synthetic diamond bases grown by modified CVD, which were $\sim 12 \times 2.5 \times 0.3$ mm in dimensions or smaller and were pressed into copper heat sinks, so that only one or two of their surfaces could be processed.

For cw pumping of LDs, we used an LDC-8-01 current source with a current setting error within ~ 1 mA. For high-power laser diode bars, it generated up to 200 ± 2 A current pulses with a duration of up to 10 ms and a repetition rate of up to 100 Hz. The output power was measured by a Coherent FM exchangeable-head power meter. If necessary, emission spectra were measured using an MDR-23 monochromator and a computer-interfaced Sony ILX512 CCD camera, which ensured a spectral resolution of ~ 0.3 Å. The thermal conductivity of the diamond bases before and after metallisation was evaluated with an accuracy of ~ 20 % by exploring heat transport across a specimen with a UKT-3 system or by the transient thermal grating technique with an LTR 266-01 laser thermorelaxometer.

3.1 Natural diamond heat sink bases

In the initial stage of our experiments, we used natural diamond heat sinks and InGaAs/AlGaAs quantum-well heterostructure LDs with a stripe width of ~ 100 μm. The thermal conductivity of the DHBs was ~ 1400 W m^{-1} K^{-1}, and they had optimal dimensions for modelling thermal processes [6].

The cw LD output power was measured as a function of drive current in a wide range, to the point of complete degradation (Fig. 1). The performance of the lasers on

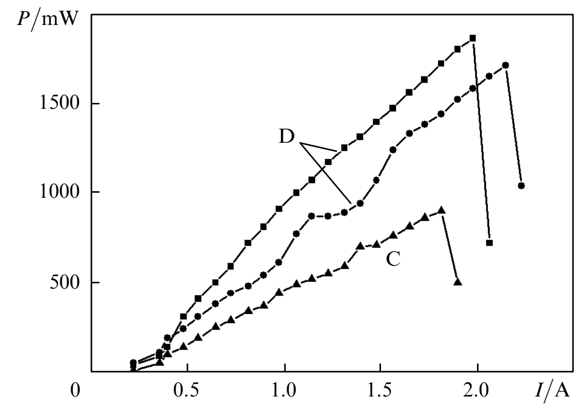

Figure 1. Power – current characteristics of laser diodes mounted on diamond bases (D) and a copper heat spreader (C) by a nonoptimised process.

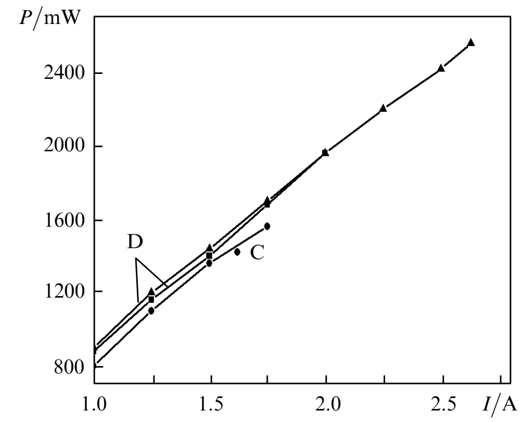

Figure 2. Power – current characteristics of LDs mounted on diamond (D) and copper (C) bases using heat treatment (optimised process).

DHBs was compared to that of devices mounted directly on a copper heat spreader under the same conditions. The laser cavity mirrors were produced by cleaving the crystal (with no dielectric coating).

Figure 1 demonstrates that, on the whole, the laser diodes on DHBs degrade at higher drive currents. The scatter in the data is probably due to the scatter in the adhesive properties of the coating, which depend on the metallisation process and influence the thermal resistance R_{th} of the device. In the case of diamond substrates, the use of an optimised mounting process reduces R_{th} on average by at least 30% (to $R_{th} \leqslant 3$ K W^{-1}). This is attributable to the better performance of the diamond heat sinks in comparison with copper due to the higher rate of heat exchange processes in the former system [6]. According to previous results [3, 4], the thermal resistance of high-power transistors can be reduced under such conditions by up to a factor of 2.5.

It also follows from Fig. 1 that the slope efficiency of the lasers mounted on DHBs by the above nonoptimised process is a factor of 1.5 – 2 higher than that of the best devices on copper bases. Estimates indicate that the wall-plug efficiency increases by about the same factor.

Taking advantage of consecutive steps capable of optimising the process of laser diode mounting on DHBs (the use of the high-temperature solder POS-61 instead of indium, annealing of the DHB after metallisation and soldering of the laser diode to the DHB under mechanical load), we were able to at least double the LD output power (Fig. 2), which correlates with results for other semiconductor devices [3, 4]. As seen in Fig. 2, the power – current characteristic of the LDs mounted on DHBs remains linear over the entire range of diode currents studied. As distinct from that of the LD on a copper heat spreader, its slope efficiency is insensitive to the optimisation of the mounting process. The power – current characteristic of one of the best LDs on copper heat spreaders saturates at a current as low as ~ 1.8 A, which may be due to the lower thermal conductivity of copper compared to the DHBs and the increase in the R_{th} of the device at high diode currents.

Note that the thermal conductivity, melting point and strength of POS-61 exceed those of indium, which is essential for improving the reliability, operational life and stability of high-power LDs, especially at high ambient temperatures.

3.2 Synthetic diamond heat sink bases

We also tested synthetic diamond heat sinks in combination with LDs similar to those described above. The thermal conductivity of the unmetallised DHBs used in our experiments was measured to be 600 – 1400 W m^{-1} K^{-1}. The LDs mounted on the synthetic diamond heat sink bases metallised by ion beam sputtering were similar in performance parameters to those on natural diamond heat sinks with a thermal conductivity of $\sim$ 1400 W m^{-1} K^{-1}. Adhesion tests showed that the samples ranged in adhesion strength from 5 to 30 MPa. The scatter for a given sample was within 30 % and depended on the film deposition conditions and soldering process. The resistivity of the films was no higher than 1 Ω cm.

3.3 Pulsed diode bars on DHBs

We compared the performance of laser diode bars on diamond and copper substrates. To this end, 30-W InGaAs/AlGaAs/GaAs diode bars with a length of 2 – 3 mm, emitting millisecond pulses at 810 nm, were studied in a wide range of pump pulse amplitudes (up to 100 A) at a pulse repetition rate of 10 Hz or higher. We used DHBs produced from polycrystals grown by modified CVD. The diamond bases were bonded to copper substrates either via conventional metallisation followed by soldering, or by a simplified process: pressing into copper. The power – current characteristics of the diode bars mounted on polycrystalline DHBs, synthetic single crystals and copper

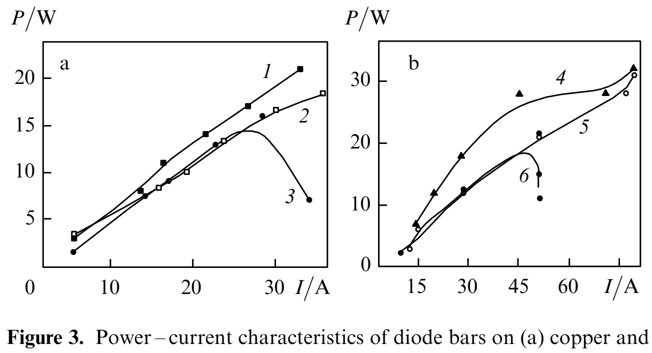

Figure 3. Power – current characteristics of diode bars on (a) copper and (b) diamond bases at current pulse durations of (*1*) 30, (*2*) 50, (*3*) 100 and (*4–6*) 500 – 1000 μs (*1–4*) before and (*5*, *6*) after operation for a time.

bases (Fig. 3) demonstrate that, at pulse repetition rates of 10 Hz, the diode bars on diamond heat sinks are capable of operating at pulse durations of up to 1000 μs, whereas, all other parameters being the same, the pump pulse duration for the diode bars on copper bases is limited by 100 μs.

Note that the single-crystal DHBs proved the most effective. Comparable or slightly poorer results were obtained when polycrystals were pressed into copper, but this approach is easier to implement and requires less effort. Using a combination of liquid-cooled microchannel heat sinks and DHBs [Fig. 3b, curves (*4*), (*5*)], we were able to extend the drive current range of diode bars by a factor of 2 – 3 at a pulse repetition rate of 10 Hz and millisecond pulse durations. Our results demonstrate that diamond is an attractive heat sink material for high-power LD bars and other structures based on injection lasers.

4. Conclusions

We have developed a process for producing high-adhesion metallic coatings which enables the fabrication of laser diode structures with improved performance parameters on highly effective natural and synthetic diamond heat sinks. The mounting of cw laser diodes on DHBs by a non-optimised process increases their power output by up to a factor of 2, considerably extends the linear (working) portion of their power – current characteristic and increases their slope efficiency by a factor of 1.5 – 2 relative to that of LDs on copper heat sinks. Optimisation of the mounting process increases the slope efficiency only in the case of copper bases. The use of diamond heat sink bases extends the drive current range of pulsed diode bars by a factor of 2 – 3 and enables them to operate at more than one order of magnitude longer pump pulse durations (up to milliseconds) when the pulse repetition rate exceeds 10 Hz.

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