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# THERMAL RESISTANCE OF RIDGE-WAVEGUIDE LASER DIODES BASED ON GaAs, GaSb OR InP

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The effects of different substrates (GaAs, GaSb and InP) on the thermal properties of laser diodes with a ridge-waveguide structure are presented. Laser diodes with the same basic geometry exhibit different thermal resistances. The reason is therefore the difference in thermal conductivity of the substrates and the active layer compounds. This leads to different temperature distributions in the structures. The theoretical results were supported by experimental data.

Laser diodes in the wavelength range of 0.85 $\mu$m, 1.3 $\mu$m, 1.55 $\mu$m or 2.3 $\mu$m are of growing interest as light sources for different applications in communication and measurement. Such devices are based on GaAs, InP or GaSb substrates. The emission wavelength is determined by a ternary or quaternary compound layer. This active layer and the surrounding confinement layers are grown in an epitaxial process via the liquid or vapor phase. Lateral structuring and metallization yield laser diodes with a low threshold current and a high output power. One proposal is a device with a ridge-waveguide (RW) structure. A ridge (of 2-6 $\mu$m width) between two grooves is designed by etching through a mask. This RW laser diode exhibits good and simple current and light confinement. Since the temperature rise in the device under operation affects both device parameters and lifetime, we have investigated the temperature distribution in RW laser diodes.

## Ridge-waveguide structure laser diodes

The RW structure can be manufactured in a simple technological process. After epitaxy, a ridge is formed by wet chemical etching through a

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photolithography mask down to an etch stop layer. The grooves left and right of the ridge and the area outside the grooves are covered with oxide. Thus, the Ti/Au metallization is in contact only with the top of the ridge. Cleaved chips were mounted *p*-side down on heat sinks for measurements.

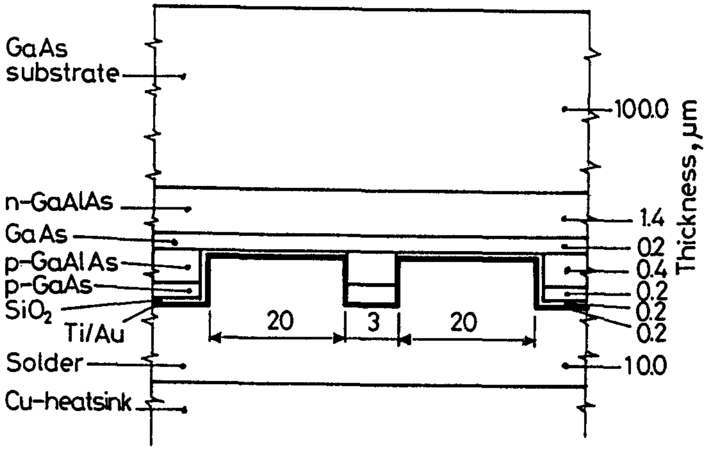

Fig. 1 Schema of the RW laser diode based on GaAs

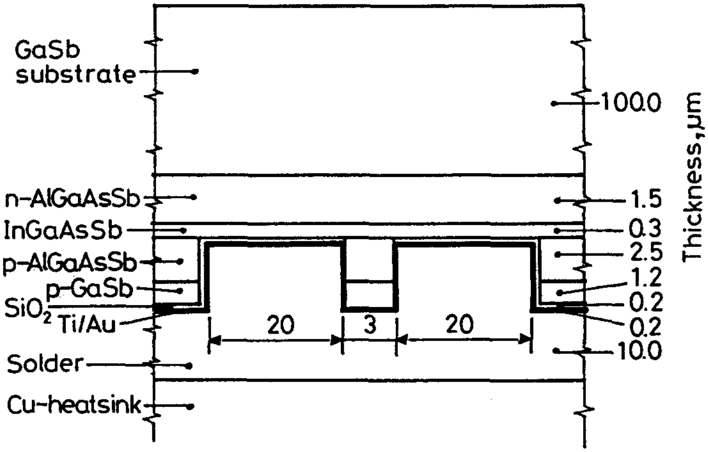

Fig. 2 Schema of the RW laser diode based on GaSb

The schemes of the RW structures based on GaAs, GaSb and InP are shown in Figs 1-3. Besides the geometry, the thermal conductivity is a main parameter in the modelling. Table 1 gives the thermal parameters for the layers in the different devices.

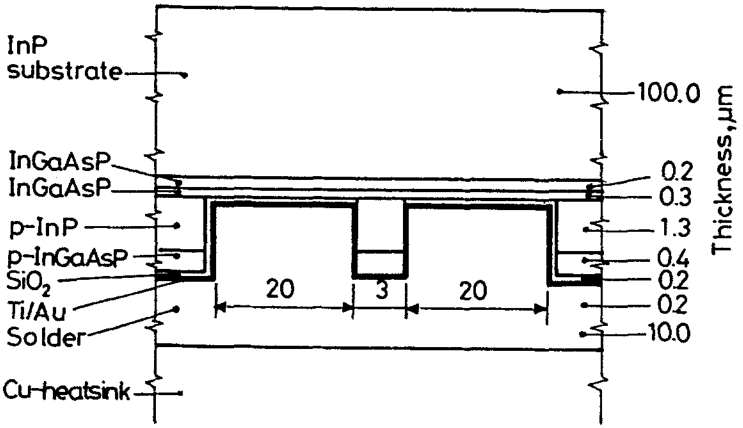

Fig. 3 Schema of the RW laser diode based on InP

Table 1 Thermal conductivities of the layers in RW laser diodes based on GaAs, GaSb or InP, W/deg·m

| Layer | GaAs | | GaSb | InP |
|---|---|---|---|---|
| Substrate | GaAs | | GaSb | InP |
| | 39 [1] | | 31 [2] | 88 [3] |
| Confinement layer | GaAlAs | | AlGaAsSb | |
| | 12 [1] | | 9.1 [2] | |
| Active layer | GaAs | | InGaAsSb | InGaAsP |
| | 39 | | 10.5 [2] | 4.5 [3] |
| Etch stop layer | - | | - | InGaAsP |
| | | | | 5.2 [3] |
| Confinement layer | GaAlAs | | AlGaAsSb | InP |
| | 12 | | 9.1 | 88 |
| Contact layer | GaAs | | GaSb | InGaAsP |
| | 39 | | 31 | 5.2 |
| Isolator | | $SiO_2$, | 2 | |
| Metallizaton | | Ti/Au, | 300 | |
| Solder | | SnPbIn, | 25 [4] | |

For the modelling, the same basic device geometry and operating conditions (driving current) were used in all cases. For the calculation, a chip length $L = 200\,\mu m$, a width $B = 400\,\mu m$ and a substrate thickness $T = 100\,\mu m$ were standard. The ridge width is $w = 3\,\mu m$, and the grooves are $20\,\mu m$ wide.

## Theory

### *Calculation of the temperature distribution*

The temperature distribution $T(x,y)$ perpendicular to the ridge is obtained as the numerical solution of the stationary thermal conduction equation [5]. Two heat sources are taken into account:

a) the active region of the laser diode with the heat power $P_{pn} = U_{pn}I$ ($U_{pn}$ = voltage drop in the active region, $I$ = injection current);

b) the metal-semiconductor contact layer at the top of the ridge with the heat power $P_c = R_cI^2$ ($R_c$ = ohmic resistance of the contact).

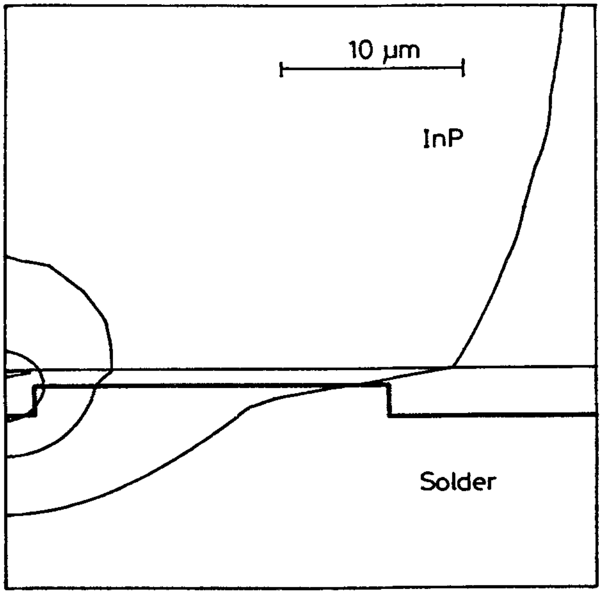

**Fig. 4a** Temperature distribution $T(x,y)$ of RW laser diodes perpendicular to the ridge in a half cross section $I = 50$ mA, $R_c = 5\ \Omega$, Isothermes distance 0.5 deg.
a) InP substrate, $U_{pn} = 0.95$ V, $\Delta T_{pn} = 4.5$ deg, $R_{th} = 81$ deg/W

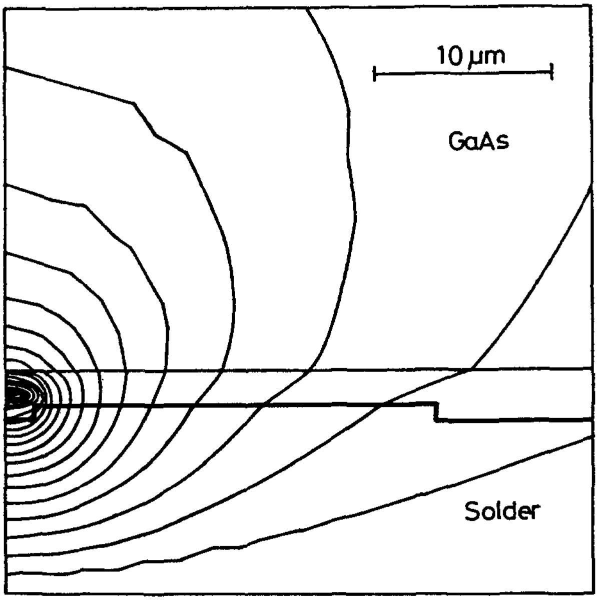

**Fig. 4b** Temperature distribution $T(x,y)$ of RW laser diodes perpendicular to the ridge in a half cross section $I$ = 50 mA, $R_c$ = 5 Ω, Isothermes distance 0.5 deg.
b) GaAs substrate, $U_{pn}$ = 1.45 V, $\Delta T_{pn}$ = 10.2 deg, $R_{th}$ = 127 deg/W

The device symmetry permits reduction of the calculations to one half of the chip cross-section only. The resulting temperature distributions for the three RW structures correspond to unique injection currents ($I$ = 50 mA) and contact resistances ($R_c$ = 5 Ω), whereas the voltage drops $U_{pn}$ differ from each other (see Fig.4). It is clearly shown that the InP structure (Fig. 4a) exhibits the smallest temperature rise $\Delta I_{pn}$ from the copper heat sink to the active region. Differently from the other structures, the InP substrate conducts many times more heat power to the sink than the ridge. In the GaAs structure (Fig. 4b), the greatest value of $U_{pn}$ occurs and so the temperature drops by the maximum value $\Delta I_{pn}$ = 10.2 deg, although the thermal resistance $R_{th}$ of the material is higher than in the GaSb laser (see Section 2.2).

### *Equivalent circuit model*

Models of heat conduction problems often use the equivalent electrical method, replacing voltage, current and electrical resistance by temperature drop, heat flux and thermal resistance. The latter is a parameter of the material which is actually independent of the heat power value, but not of the heat power distribution. In the simple case of only one uniform heat source in the active region, the total thermal resistance of the laser chip mounted on the heat sink is given usually by

$$R_{\mathrm{th}}\Big|_{P_c=0} = \Delta T_{\mathrm{pn}} / P_{\mathrm{pn}} \tag{1}$$

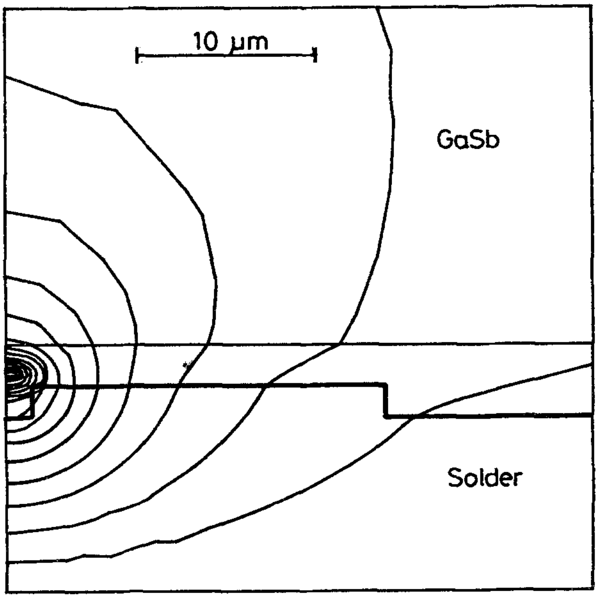

**Fig. 4c** Temperature distribution $T(x,y)$ of RW laser diodes perpendicular to the ridge in a half cross section $I$ = 50 mA, $R_c$ = 5 Ω, Isothermes distance 0.5 deg.
c) GaSb substrate, $U_{\mathrm{pn}} = 0.87$ V, $\Delta T_{\mathrm{pn}} = 8.4$ deg, $R_{\mathrm{th}} = 193$ deg/W

$R_{\mathrm{th}}$ describes the average thermal properties of all heat paths between the active region and the heat sink. If the injection current is limited to small values of about 20 mA, or the electrical resistance $R_{\mathrm{c}}$ vanishes, the contact heating can be neglected and Eq. (1) leads to the temperature rise $\Delta T_{\mathrm{pn}}$ to a good approximation. For this purpose, the thermal resistances $R_{\mathrm{th}}$ in the description of Fig. 4 are determined from temperature calculations with a single heat source in the active region.

Table 2 demonstrates the dependence of the thermal resistance $R_{th}$ on some structural modifications.

Table 2 shows that in all cases an increasing ridge width lowers the $R_{th}$ value because of the greater starting areas of heat conduction. Further, the thickness and the conductivity of the solder layer exert a strong influence on the thermal resistance. If the solder conductivity value of 25 W/m·deg is deteriorated by microscopic voids, for instance, a drastic increase in $R_{th}$ may result, whereas the application of pure In solder ($\lambda s$ = 87 W/m·deg) would lower the thermal resistance $R_{th}$ clearly.

**Table 2** Thermal resistances $R_{th}$ for some parameter variations of the RW structures (standard values: ridge width $w = 3\,\mu m$, solder thickness $d_s = 10\,\mu m$, solder conductivity $\lambda s$ = 25 W/m·deg

| Variation | $R_{th}$, deg/W | InP | GaAs | GaSb |
|---|---|---|---|---|
| | | 81 | 127 | 193 |
| $w = 2\,\mu m$ | | 95 | 145 | 215 |
| $w = 5\,\mu m$ | | 67 | 105 | 159 |
| $d_s = 1\,\mu m$ | | 62 | 81 | 155 |
| $d_s = 20\,\mu m$ | | 92 | 146 | 210 |
| $\lambda_s$ = 10 W/m·deg | | 102 | 176 | 243 |
| $\lambda_s$ = 87 W/m·deg | | 60 | 86 | 152 |

Variations of some other structural parameters of the laser chip (substrate thickness, thicknesses of the etch stopping layer and the cap layer, as well as the widths of the chip and the channels) by a factor of 2 change the thermal resistance by not more than by 6% in the case of InP [5].

In practice, a higher injection current $I$ or ohmic resistance $R_c$ of the contact can lead to a relevant contact heating. Considering a second heat source at the contact, Eq. (1) is no longer valid for transforming between the calculated (or measured) temperature $\Delta T_{pn}$ and the thermal resistance $R_{th}$ and has to be replaced by a rather complex expression. One part of the contact heat flows through the active region and the substrate to the heat sink, whereas the other part reaches the sink directly through the solder. Only the first path influences the active region temperature rise $\Delta T_{pn}$. The relation of the two power parts depends on the thermal resistances of both heat paths from the contact to the sink. At least three thermal resistances are needed in the equivalent circuit to describe this situation (Fig. 5). The always known thermal resistance $R_{th}$ of the total heat path from the active region to the sink is related to the resistances in Fig. 5 by

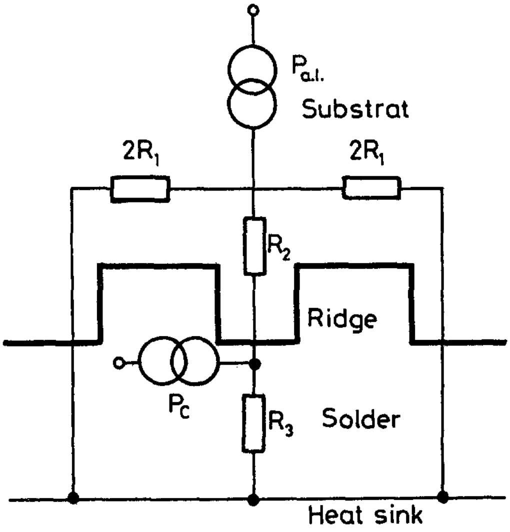

**Fig. 5** Equivalent thermal circuit of the RW laser diode with two heat sources: active region $P_{pn}$, contact $P_c$ and thermal resistances of the different heat paths $R_n$

$$R_{th}^{-1} = R_1^{-1} + (R_2 + R_3)^{-1} \tag{2}$$

The corresponding temperature drop can be expressed by means of wiring diagram analysis:

$$\Delta T_{pn} = R_1 \left(P_{pn} - \frac{R_1 P_{pn} - R_3 P_c}{R_1 + R_2 + R_3}\right) \tag{3}$$

Equation (3) allows a fitting to measured characteristics $\Delta T_{pn}(I)$ if the thermal resistances $R_1$, $R_2$ and $R_3$ in Fig. 5 are known. The ridge resistance $R_2$ is immediately given as

$$R_2 = \sum_{\text{ridge}} d_1 / (w \cdot L \cdot \lambda_1) \tag{4}$$

($L$ = laser length). The resistances of the substrate ($R_1$) and the solder ($R_3$) are determined from calculations of the temperature rise $\Delta T_{pn}$ in different cases [5]. The results are shown in Table 3.

**Table 3** Calculated values of the thermal resistances in the equivalent circuit (Fig. 6)

| Thermal resistances, deg/W | | InP | GaAs | GaSb |
|---|---|---|---|---|
| substrate path | $R_1$ = | 91 | 242 | 299 |
| ridge path | $R_2$ = | 318 | 99 | 353 |
| solder path | $R_3$ = | 390 | 166 | 188 |
| | $R_{th}$ = | 81 | 127 | 192 |

The results in Table 3 allow a rough analysis of the heat paths inside the laser structures. The relation of the resistances $R_1$, $R_2$ and $R_3$ shows that in the InP laser 89% of the heat generated in the active region flows through the substrate to the sink, whereas only 51% of the contact heat reaches the sink directly through the solder layer. In the GaAs structure, these values are 52% and 67%, while in the case of GaSb they are 64% and 78%, respectively. The simple form of the equivalent circuit in Fig. 5 neglects connections between the heat paths assumed, for instance the heat flux through the walls of the ridge. Therefore, some discrepancies occur in Table 3, especially the strongly different solder resistances $R_3$. Nevertheless, the thermal resistances $R_1$, $R_2$ and $R_3$ lead with Eq. (3) to a temperature rise $\Delta T_{pn}$ for any injection current $I$ (for $I$ = 50 mA, see Fig. 4). The good agreement between these values and the results computed above justifies the application of the equivalent circuit of Fig. 5.

## Experimental investigation

In order to test the equivalent thermal circuit, different mountings of the laser diodes were performed. Besides ordinary soldering (p-down at a copper heat sink), only one half of a laser diode was soldered at the heat sink or the laser chip was soldered above a groove, so that the ridge and the graves of the RW laser diode were not wetted by the solder. The results of measurements can be compared with the total thermal resistance and the substrate resistance $R_1$ in the equivalent thermal circuit (Fig. 5). For the experiments, we used InGaAsP/InP RW laser diodes.

**Table 4** Theoretical and experimental results for resistances (in deg/W) of the equivalent thermal circuit for InGaAsP/InP RW laser diodes with $w$ = 6 $\mu$m [6]

| Resistance | Theory | Experiment |
|---|---|---|
| $2R_1$ | 150 | 156-165 (half-soldered) |
| $R_1$ | 75 | 80- 82 (groove free of solder) |
| $R_{th}$ | 63 | 65- 75 (ordinary) |

The experiments confirm well the model results (the result for the half-soldered RW laser diode is slightly larger than predicted because the model value was taken from the ordinary case).

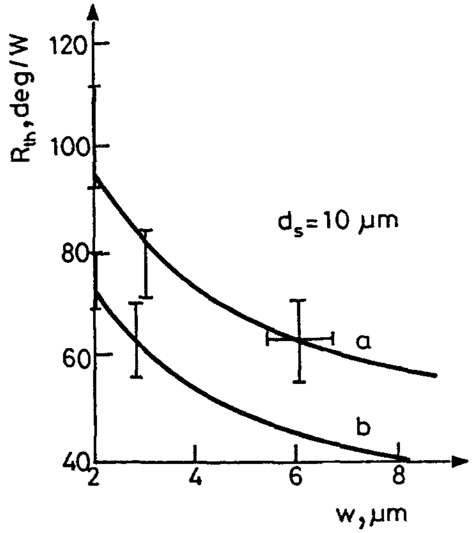

**Fig. 6** Thermal resistance of InGaAsP/InP RW laser diodes for various ridge widths $w$,
a) mounting with SnPbIn-solder
b) mounting with In-solder, theoretical curves for a solder thickness $d_s = 10$ µm, exp. results

As shown theoretically, the thermal properties of the solder layer strongly affect the temperature distribution in the structure. The use of a solder material with a high thermal conductivity (e.g. In with 87 W/deg·m) would decrease the thermal resistance by 20 to 40 deg/W. This was verified experimentally. Figure 6 presents results for InGaAsP/InP RW laser diodes soldered with SnPbIn or with In p-side down on a copper heat sink. With increasing ridge width, the thermal resistance decreases, but the difference between the two ways of mounting is stable at about 20 deg/W. The case of p-side up mounting was also investigated and reported in a previous paper [5].

## Conclusion

Our investigations demonstrated the effects of the thermal properties of different substrate materials on the temperature distribution in laser diodes with a RW structure. The high thermal conductivity of the InP substrate permits the flow of about 80% of the heating power to the heat sink. In RW structures based on GaAs or GaSb, this part is much smaller because of their lower thermal conductivity compared with that of InP. The mounting process of laser diodes with the same structure influences the total thermal resistance $R_{th}$ strongly.

With a proper design, the thermal resistance may be decreased by 20-40 deg/W through the use of a solder with a high thermal conductivity. The decrease is due to the improvement in heat flux through the broad area substrate to the heat sink.

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**Zusammenfassung** — Es wurde der Einfluß verschiedener Substrate (GaAs, GaSb und InP) auf die thermischen Eigenschaften von Laserdioden mit gefurchter Hohlleiterstruktur untersucht. Laserdioden mit dem gleichen geometrischen Grundaufbau zeigen verschiedene Wärmewiderstände. Die Ursache ist folglich der Unterschied in der Wärmeleitfähigkeit der Substrate und der Verbindungen der aktiven Schicht. Dies führt zu einer unterschiedlichen Temperaturverteilung in der Strukturen. Theoretische Ergebnisse werden durch experimentelle Daten bekräftigt.