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MEASUREMENT OF THE THERMAL IMPEDANCE OF LASER DIODES VIA THERMAL TRANSIENTS

W. Both

CENTRAL INSTITUTE OF OPTICS AND SPECTROSCOPY,
ACADEMY OF SCIENCES OF THE GDR,
RUDOWER CHAUSSEE 6, BERLIN DDR-1199

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The thermal impedance of laser diodes was determined by the measurement of thermal transients. The parameters of an equivalent R–C network were synthesized from the transient response. The network was compared with the real layer structure of the device. The effects of structure, mounting and aging on the temperature distribution were investigated with this method.

To investigate the heat generation and the heat flux in semiconductor devices, modelling is often used. Because of the complexity of the three-dimensional heat flux in multilayer structures, the solution for the steady and transient cases is searched numerically after simplification of the boundary conditions [1–3[. Another possibility is the numerical evaluation of the experimental data of a heating process in a semiconductor device. This is based on the exponential function as the transient solution of the heat flux equation [4–7]. From this, an equivalent thermal circuit can be synthesized in which the components are connected with the thermal impedances of the device structure [8, 9]. With this method, laser diodes were analysed from a thermal point of view.

Thermal modelling

The electrical modelling of mechanical or thermal processes is a known method. It is based on the formal conformity of differential equations describing the transient phenomenon. The differential equation for the heat flux transient after FOURIER,

$$dT/dt = \lambda/C \cdot \varrho \, d^2T/dx^2 \tag{1}$$

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has the same structure as the cable equation (voltage drop at an R–C cable) in communication theory:

$$dU/dt = 1/(r'c')\, d^2U/dx^2 \tag{2}$$

where
T = temperature
t = time,
λ = thermal conductivity,
C = specific heat capacity,
ϱ = density,
U = voltage,
r' = resistance per unit length,
c' = capacity per unit length, and
x = length.

Thus, an equivalent description of thermal processes with electrical models and concepts of electric engineering is possible [10]. This is called a thermo-electrical analogue.

Equivalent thermal circuit

In the following considerations, this thermo-electrical analogue is the basis for the development of an electrical equivalent circuit. Therefore, concepts of the theory of linear networks and systems are used. The modelling of Eq. (2) is possible after discretement of the place coordinate x. This converts the differential quotients into difference quotients and the homogeneous cable can be separated in a ladder network. The single quadripole of an infinitesimal cable section is a four-port of the heat capacitance and the thermal resistance. The components of the cascade are connected with fixed sections of the cable (Fig. 1). The electrical model of the composed heat conductor is a ladder network. Measurement points in the network are identical with fixed sections of the conductor. Hence, this model is called a physical relevant model [8]. The steady thermal resistance is calculated via the temperature difference ΔT between the measuring point and the ambient

$$R_{th} = \Delta T/P = (T_i - T_a)/P \tag{3}$$

where P = power.

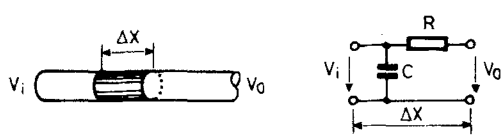

Fig. 1 Equivalent circuit of a cable section x

If the ambient temperature T_a is used as a reference, it can be set to zero through calculation with temperature differences. In the network, this means a short circuit at the output. From the input, the network is now a linear two-pole.

Synthesis of the equivalent circuit from measured data

To test the thermal reaction of a semiconductor device, it is loaded with a step current pulse. The reaction of the test object, i.e. its response to the step pulse, is called transient thermal resistance $z(t)$. The step pulse is deformed by the transfer function of the ladder network. The step pulse response of the first four-port C_1, R_1 of the network in Fig. 2 is an exponential function. This response is deformed by the next *R–C-* four-port, and so on to the end of the network. The single four-ports in Fig. 2 represent sections of the multilayer heat conductor. Because of the finite

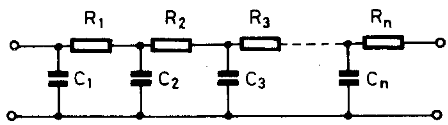

Fig. 2 Equivalent circuit of the multilayer heat conductor, ladder network after CAUER

thickness, the thermal pulse has a finite transition time through the layer. This delay is determined by the thermal diffusivity and the thickness of the layer. The step pulse response $z(t)$ can be approximated by the statement

$$z(t) = 1/P\sum_j \Delta T_j(1-\exp(-t/\tau_j)) \tag{4}$$

This mathematical statement allows the development of a further network. A series circuit of parallel *R–C* components also causes the response in Eq. (4). This two-pole network is shown in Fig. 3. The components R_j and C_j can be determined by

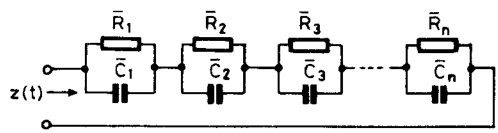

Fig. 3 Network, described by the approximation equation (4) for the transient thermal resistance $z(t)$, network after FORSTER

means of Eq. (3) and the time constant τ_j

$$\tau_j = R_jC_j \tag{5}$$

The networks (Figs 2 and 3) are electrically identical networks and their components can be transferred into each other. The resistances and capacitances of one network are a function of all components of the other network. The components of the ladder network can be determined with a chain fraction calculation of the polynomial of the transfer characteristics of the network after FORSTER (Fig. 3). Because of the number of layers, i.e. elements in the cascade, it is reasonable to perform this calculation with a computer. The algorithm for the transformation of the networks is known from the theory of linear networks and has been described in the literature (see e.g. [11]).

Measurement

The method for the determination of the thermal impedance of laser diodes was presented in a previous paper [12]. It is based on the temperature-dependence of the voltage drop at the $p-n$ junction of a diode [13].The temperature coefficient $\mathrm{d}V/\mathrm{d}T$ for GaAs was given in [14]. In this paper it was determined for GaAlAs/GaAs and InGaAsP/InP. As shown in Fig. 4, it is identical with the coefficients of Si, Ge and GaAs, i.e. this coefficient is a physical constant for semiconductor $p-n$ junctions.

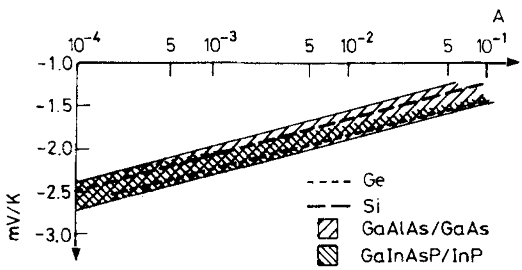

Fig. 4 Measured temperature coefficient $\mathrm{d}V/\mathrm{d}T$ of the voltage drop at the $p-n$-junction of Ge-, Si-diodes (13), GaAlAs/GaAs and InGaAsP/InP diodes at RT

For the measurement, the device is loaded with a constant current pulse ($t_i > 1$ ms). During the pulse, the voltage at the $p-n$ junction drops due to the heating and this transient is recorded. Because the temperature coefficient is negative, the voltage is inverse to the temperature:

$$\Delta T = -\mathrm{d}T/\mathrm{d}V \cdot \Delta V \tag{6}$$

Putting Eq. (6) into Eq. (4) approximates the measured voltage transient:

$$z(t) = 1/P \sum_j \mathrm{d}T/\mathrm{d}V \, \Delta V (\exp(-t/\tau_j) - 1) \tag{7}$$

The voltage transients at the devices were recorded in the time range 10^{-7}–10^{-3} sec. Figure 5 shows typical measured curves in the log-log scale to be analysed.

Approximation of the measured values

The analytical values of the exp functions can be determined from the measured values by means of different methods. On the one hand, the squared error sum of the measured values and approximation is minimized by inner regression [5, 7, 15]. On the other hand, the analytical values can be determined by linear regression calculation of the logarithmic measured values [4, 6]. Both methods need a computer calculation. For several reasons, the linear regression was used here. As may be seen in Fig. 5, the single exp functions are clearly separated from each other. Thus, there is no danger that some data are lost. This method gives the number of exp functions directly without iteration calculation.

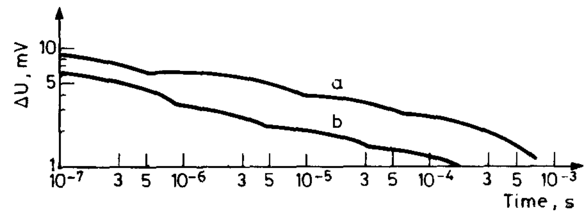

Fig. 5 Transient voltage drop at GaAlAs/GaAs (a) and InGaAsP/InP (b) diodes after switching on a step current pulse, $I_F = 80$ mA

The calculation of the analytical values of the exp functions is performed with a computer program in BASIC, in which the linear regression calculation is a subroutine. The analytical values are given to a transformation procedure which converts the synthesized network after FORSTER into the ladder network after CAUER. The results are the values of the thermal resistance and heat capacitances in an *n*-section network of *R–C* quadripoles.

Results

The investigation was especially performed to test different laser diode mountings and the control contact degradation. To identify the single exp functions, as shown in Fig. 5, the measurements were made under several mouting conditions. In Fig. 6, the transient temperature rise of a clamped and soldered GaAlAs/GaAs laser diode [16] is shown. By means of a one-dimensional evaluation of the heat flux in the multilayer structure, the place coordinate x can be given, too [17].

The following typical analytical values of the exp functions were determined (Table 1).

These time constants agree well with the results of modellings and measurements

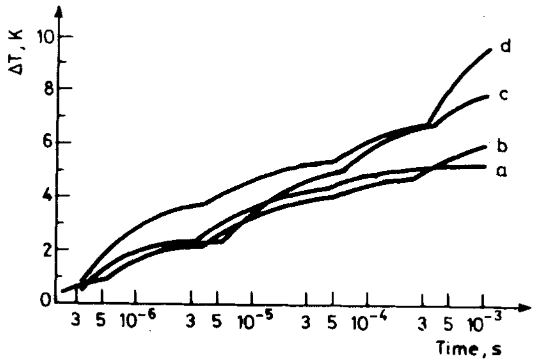

Fig. 6 Transient temperature rise at the $p-n$-junction of a GaAlAs/GaAs laser diode, I_F = 80 mA. Curve d) clamped on a copper submount; a) soldered p-down on a copper submount; b) soldered p-down on a silicon submount; c) soldered p-up on a copper submount

Table 1 Typical analytical values of the exp functions for GaAlAs/GaAs laser diodes

	R, K/W	τ/μ s
Chip	12–20	1– 3
Chip	7–13	12– 20
Solder	7–10	80–120
Si submount	18–22	350–450

in the literature [18–20]. With these values, the components of the ladder network (Fig. 2) were calculated (Table 2).

InGaAsP/InP laser diodes [21] were investigated in the same manner. Because of the low T_0 value, these devices are very sensitive to temperature rise. Thus, it is important to minimize their thermal resistance. The thermal conductivity of the quaternary alloy is much worse than that of the InP substrate [22]. Accordingly, mesa-structures are thermally advantageous as compared to planar structures.

Table 2 Thermal resistances and heat capacitances of the equivalent thermal network (Fig. 2) for GaAlAs/GaAs laser diodes

	C_{th}, Ws/K	R_{th}, K/W	
Chip	$0.6–1.7 \cdot 10^{-7}$	16–23	
Chip	$0.8–1.2 \cdot 10^{-6}$	12–18	
Solder	$1.0–1.5 \cdot 10^{-5}$	8–11	
Si submount	$4 – 6 \cdot 10^{-5}$	10–12	
Substrate	$9 \cdot 10^{-6}$	22–26	(p-up mounting only)

Figure 7 shows the influence of different mountings on the transient temperature rise. The single exp functions were identified here, too.

The values in Table 3 were transformed in the thermal resistances and heat capacitances of the equivalent circuit.

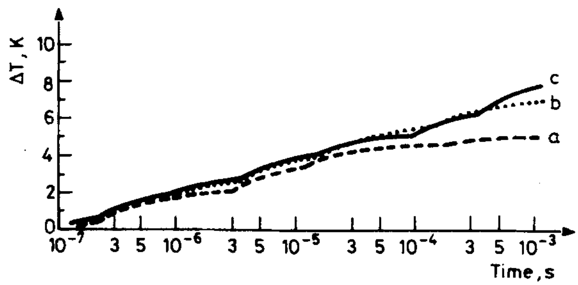

Fig. 7 Transient temperature rise at the $p-n$-junction of a InGaAsP/InP laser diode, $I_F = 30$ mA. Curve a) soldered p-down on a copper submount; b) soldered p-up on a copper submount; c) soldered p-down on a silicon submount

Table 3 Typical analytical values of the exp functions for InGaAsP/InP laser diodes

	R, K/W	τ/μ s
Chip	20–40	1– 2
Chip	10–12	10– 17
Solder	7–15	70–110

Table 4 Thermal resistances and heat capacitances of the equivalent thermal circuit (Fig. 2) for InGaAsP/InP laser diodes

	C_{th}, Ws/K	R_{th}, K/W	
Chip	$0.5–1.5 \cdot 10^{-7}$	25–35	
Chip	$1.0 \cdot 10^{-6}$	12–18	
Solder	$0.8–1.3 \cdot 10^{-5}$	13–22	
InP substrate	$0.7–1.0 \cdot 10^{-5}$	10–15	(p-up mounting only)

The total thermal resistance fits well with published results [23, 24].

After aging tests, we observed an increase in the thermal resistance. The reason for this increase is the metallurgical reaction between the gold and solder. The growth of an intermetallic compound layer leads to an increase in the thermal resistance, because its thermal conductivity is bad [25]. As shown in Fig. 8, the interlayer can be observed by this means.

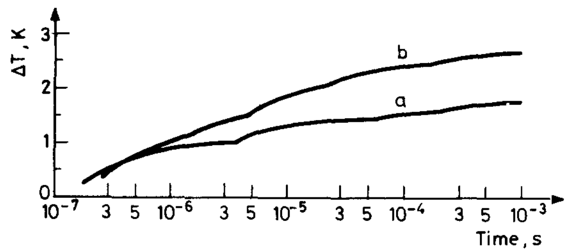

Fig. 8 Transient temperature rise of a GaAlAs/GaAs laser diode before a) and after b) aging 100 h (50 °C) 100 mA, $I_F = 80$ mA

With this method, it is also possible to check the technological quality of the mounting of the devices in the production process. The quality of soldering can be investigated simply by comparing the voltage transient with a standard transient curve. With a computer, it is possible to automate the quality control (CAQ). Figure 9 shows the transient heating of a well and a badly soldered laser diode. The bad soldering feeds back on the thermal impedance of the laser structure ($t < 5 \cdot 10^{-6}$ sec). The transient for $t > 5 \cdot 10^{-6}$ sec represents the intermetallic

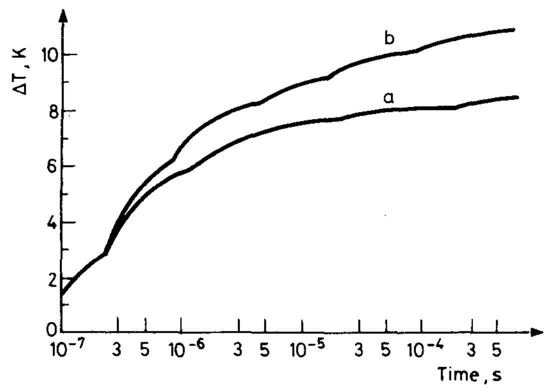

Fig. 9 Transient temperature rise at the $p-n$-junction of a good soldered a) and a bad soldered b) GaAlAs/GaAs laser diode, $I_F = 30$ mA

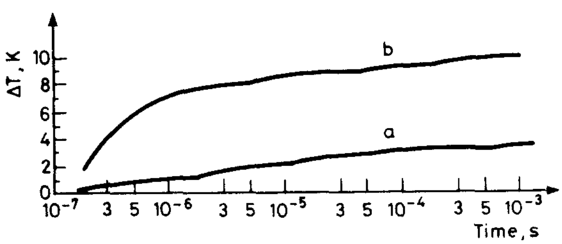

Fig. 10 Transient temperature rise of GaAlAs/GaAs laser diode with shallow a) and deep b) zinc-diffusion, $I_F = 30$ mA

compound layer, and the transient for $t > 2 \cdot 10^{-5}$ sec the solder layer. In the equivalent ladder network, the thermal resistance of the intermetallic compound layer is 8.3 and 8.9 K/W for the well and badly soldered laser diode, and the thermal resistance values for the solder layer are 8.3 and 16.4 K/W. The metallographic inspection of the solder joint showed a nearly 2 μm thick intermetallic compound layer and voids in the solder of the badly soldered device.

Because of a fault in one wafer, the zinc was diffused too deep. Therefore, the internal efficiency was low (50%) and the nonradiative recombination caused additional inner heating. Its transient temperature rise can be seen in Fig. 10 with a very short time constant of about 300 nsec.

References

1 W. Nakwaski, Electron Technol., 10 (1977) 1.
2 W. Nakwaski, IEEE Proc. P.I., 121 (1984) 3.
3 V. Ranamurthy, P. K. Chaturvedi and D. Kakati, Solid state electronics, 24 (1981).
4 C. Mauersberger, Elektrie, 22 (1968) 3.
5 W. Köchli, Thesis, ETH Zürich, 1969.
6 W. Büttner, Arch. Elektrotechn., 59 (1977) 6.
7 R. Sandau, Z. Elektr. Inform.- u. Energietechn., 11 (1981) 3.
8 H. Müller, Arch. Elektrotechn.. 54 (1971) 3.
9 W. Ameling and K. Daffner, Arch. Elektrotechn., 66 (1983) 3.
10 L. Beuken, Wärmeverluste in periodisch betriebenen Öfen, Thesis. Bergakademie Freberg, 1936.
11 G. Wunsch, Theorie und Anwendung linearer Netzwerke, Akadem. Verlagsgesell., Leipzig 1961.
12 W. Both, Z. Elektr. Inform.- u. Energietechn., 12 (1982) 6.
13 J. H. Simpson, SCP & Solid State Techn., 7 (1964) 9; 7 (1964) 10.
14 B. G. Cohen, W. B. Snow and A. R. Tretola, Rev. Sci. Instrum., 34 (1963) 10.
15 J. H. Scharf and J. Peil, EIK, 8 (1972) 8.
16 H. Bachert, W. Pittroff, I. Rechenberg, S. Stoeff and K. Vogel, Phys. Stat. Sol., 94 (1986) 1.
17 J. J. Hughes, D. B. Gilbert and F. Z. Hawrylo, RCA Rev., 46 (1985) 6.
18 M. Suyama, N. Ogasawa and R. Ito, Jap. J. Appl. Phys., 20 (1981) 6.
19 P. Melman and W. J. Carlsen, Appl. Optics, 20 (1981) 15.
20 M. Ito and T. Kimura, IEEE J. Quant. Electr., QE-17 (1981) 5.
21 H. Bachert, J. Frahm, K. Vogel and G. Wagner, 1.3 μm index guide lasers for fiber optic communication 2. Con. on Physics and Technology of GaAs and other III–V semiconductors, Budapest, 8–11 Sept. 1986, p. 102.
22 W. Both, V. Gottschalch and G. Wagner, Cryst. Res. Technol., 21 (1986) 5.
23 M. Ohtsu, H. Tagawa and H. Kotani, Jap. J. Appl. Phys., 22 (1983) 12.
24 M. C. Amann and B. Stegmüller, Appl. Phys. Lett., 48 (1986) 16.
25 W. Both and R. Schließer, Feingerätetechnik, 35 (1986) 9.

Zusammenfassung — Mittels Messung thermischer Einschwingvorgänge wurde die thermische Impedanz von Laserdioden bestimmt. Auf Grundlage des Sprungverhaltens wurden die Parameter eines äquivalenten R–C-Gliedes ermittelt, das mit der wahren Schichtenstruktur verglichen wurde. Mittels dieser Methode wurde der Einfluss von Struktur, Aufbau und Alterung auf die Temperaturverteilung untersucht.

Резюме — Путем измерения термических переходов был определен термический импеданс лазерных диодов. На основе переходной характеристики были составлены параметры какой-либо эквивалентной *R–C* цепи, которая была затем сопоставлена с реальной слоистой структурой устройства. Этим методом было изучено влияние структуры, схемы монтажа и старения на температурное распределение.