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G. ASZÓDI
J. SZABON
I. JÁNOSSY
V. SZÉKELY

UNIFORM, HIGH RESOLUTION
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USING NEMATIC LIQUID CRYSTALS

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UNIFORM, HIGH RESOLUTION THERMAL MAPPING OF MICROCIRCUITS
USING NEMATIC LIQUID CRYSTALS

G. Aszódi*, J. Szabon, I. Jánossy, V. Székely**

Liquid Crystal Department, Central Research Institute for Physics
H-1525 Budapest 114, P.O.B. 49, Hungary

*Department of Semiconductors, Research Institute for
Technical Physics
H-1325 Budapest, Ujpest 1, P.O.B. 76, Hungary

**Chair for Electron Devices, Technical University of Budapest
H-1521 Budapest, Hungary

ABSTRACT

A new method for thermal mapping using nematic liquid crystals, primarily for use on microcircuits is given. This method provides an inherent thermal resolution of about 0.05 K if an appropriate mixture of two nematic liquid crystals is used in conjunction with reflected light polarizing microscopy. In fact, 0.1 K thermal resolution and a uniform maximal spatial resolution of 2-4 μm was achieved. The present method as compared with thermal mapping using cholesterics, provides in addition to the higher resolution a simple way of preparation of the sample surface and easy observability of the isothermal lines, which makes unnecessary photographic methods for evaluating the measurements.

АННОТАЦИЯ

В статье описывается новый метод термографирования с использованием нематических жидких кристаллов, который может быть применен, в первую очередь, случае микросхем. При использовании соответствующих смесей двух нематических жидких кристаллов и поляризационного микроскопа для отраженного света метод позволяет получить разрешение по температуре 0,05 К. Нами достигнуто разрешение по температуре 0,1 К и равномерное разрешение поля 2-4 мкм. По сравнению с применявшимся ранее методом, в котором используются холестерические жидкие кристаллы, преимуществом данного метода, помимо лучшего разрешения, является простота обработки поверхности и возможность удобного наблюдения изотермических линий, что исключает необходимость применения фотографического метода оценки.

KIVONAT

A cikkben egy új, nematikus folyadékkristályokat felhasználó hőmérsékletértékelési módszert írunk le, amely elsősorban mikroáramkörök esetében alkalmazható. A módszer megfelelő nematikus keverékek és reflexiós polarizációs mikroszkóp használatával 0.05 K hőmérséklet felbontást tesz lehetővé. Vizsgálatainkban 0.1 K hőmérséklet felbontást és 2-4 μm egyenletes térbeli felbontást értünk el. A jelen módszer előnye a korábbiakban alkalmazott koleszterikus folyadékkristályokat felhasználó eljárással szemben a jobb felbontáson kívül az egyszerű felület előkészítés és az izotermák könnyű megfigyelhetősége, ami szükségtelenné teszi a fényképezéssel történő kiértékelést.

INTRODUCTION

The application of cholesteric liquid crystals in thermal mapping become widespread in the past twenty years [1,2]. The application of these materials is based on the selective reflectivity of the cholesteric which is dependent on the local temperature. Cholesteric liquid crystals are widely used as a powerful tool of surface thermography in medicine, veterinary practice, criminology, the aerospace industry, electrical engineering, etc. [3]. Many applications can be found in microelectronics, e.g. in the field of microwave devices, thermally activated information displays or fault location [2]. It will be shown later that appropriate use of liquid crystal thermography can help us to solve degradation problems of microcircuits.

The cholesteric method is often cheaper and more suitable than others, e.g. than image converters or point-by-point measurements. Details on the early state of the art are given in Refs. 4,5 and Ref. 2 is an excellent review giving up-to-date applications. However, this method - though useful - gives qualitative information about the media rather than exact results [6,7].

The physical and technical limitations - or disadvantages - have been described by Ferguson [4]. He predicted an inherent spatial resolution for cholesterics of about 40 lines/mm (approximately 25 μm with a thermal resolution of about 0.1 K).

It can easily be seen from the figures [4] in articles published earlier that this method involves a strong dependence of the resolution on the surface temperature gradient. Moreover, limited observability and dependence of the wavelength of maximum scattering (the "colour" of the liquid crystal layer) both on the angle of incidence and on the angle of viewing [2] were observed. The temperature range covered by the method is in most cases in the 0-75°C range [1].

A further disadvantage is that the surface of the specimen must be non-reflecting or must be made to be nonreflecting by using a black cover film [5,6]. It is also wellknown that cholesterogenes are sensitive to contaminations absorbed from the air or from the surface of the sample [1,7,8].

By the method described in the present paper we hope to overcome all these difficulties and offer some further advantages, too. We propose to map the thermal field of surfaces of microscopic objects with the help of *phase transitions* of liquid crystals. A couple of reversible, easily observable phase transitions of liquid crystals exist, which are described in detail in the literature [8]. In our studies the nematic-isotropic and smectic A - nematic transitions have been used. By coating the surface of the object under examination with an appropriate liquid crystal the isotherms corresponding to the phase transition temperatures can be determined directly and with great precision. The nematic-isotropic transition determines an isotherm within 0.1 K; this isotherm could be localized spatially within 2-4 μm in our studies. These parameters provide a resolution essentially better than described earlier. In general we could not localize so precisely the isotherms corresponding to the smectic A - nematic transition, presumably due to the strong pretransitional effects near this transition. (The problem of resolution by liquid crystal films on microcircuits is discussed in detail in the Appendix).

The detailed thermal map of the surface could be determined either by using a set of different liquid crystal mixtures, or - more conveniently - by changing the temperature of the sample environment with a thermostat.

The sharpness of the nematic-isotropic transition line did not depend on the surface temperature gradient (except for extremely small thermal gradients; see later). This was a very important factor by means of which we could obtain an over-all high resolution of the surface temperature map.

Due to the character of the transition lines complicated evaluating methods were not necessary. The optical properties of the two phases applying polarized light are quite different, therefore it is easy to distinguish them in a polarizing microscope. (In practice the transition line can be seen using unpolarized light, too.)

Further advantages are the decreased sensitivity to absorbed impurities and the extended stability of the mixture when used over a long period of application.

A further factor was that there was no need to use a black background film painted on the sample [1,6]. This meant that we could treat more "sensitive" specimens (e.g. operating microcircuits) easily without altering in advertantly their structures.

EXPERIMENTAL

1. Materials

A mixture of two mesogenes (BDH, England) was used, viz. octylcyano-biphenyl, 8-OCB (BDH name M24) and octyl-cyanobiphenyl, 8CB (BDH name K24). The phase transition temperature were measured by differential scanning calorimetry (DSC) and by a polarizing microscope with a hot stage. The use of a Perkin-Elmer DSC-2 enabled their impurity content to be determined thermo-analytically (for details see Ref.[9]).

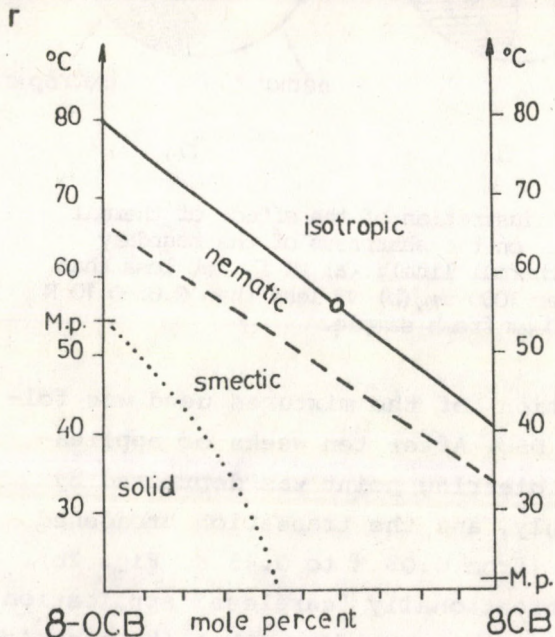


Fig. 1. Transition temperature of 8-OCB - 8CB mixtures as a function of concentration (in mole per cent). Nematic-isotropic transitions: solid line*; smectic-nematic transitions: dashed line; melting: dotted line. (*circle: transition temperature of 60 mole per cent 8CB in 8-OCB)

The sensitivity of the "clearing" transition of a liquid crystalline compound to impurity content (due to water absorption, airborne contamination, etc.) was apparent in earlier studies. A small amount (0.5-0.8 %) of impurities can

a) depress the clearing point, T_c
 b) broaden the phase transition temperature region [10].

Due to the close relation and the similar polar character of the homologous (8CB and 8-OCB) above, their mixtures behaved ideally (Fig. 1). Their nematic-isotropic transition remained sharp independently of concentration, their DSC thermograms did not indicate any

broadening (Fig. 2a, - fresh sample). As a result, from Fig. 1 one could select the optimal mixture of clearing temperature (T_c) closest to the temperature range studied.

The effect of the thermal gradient on the visibility (sharpness) of the T_c line was examined as a function of varying degrees of contamination of the materials. Whenever a thermal gradient is generated on a surface, the temperature of which is near to T_c of the material covering it, a sharp straight border-line would separate the nematic phase from the warmer isotropic phase, unless the thermal gradient was less than 0.05-0.10 K per 1000 μm . In the latter case an archipelago of nematic droplets arises the breadth of which depends on the contamination of the material (and, of course, on the thermal gradient). In other words, sharpness was faded due to excessive contamination, as illustrated in Fig. 3 (T_c -broadening). Contamination

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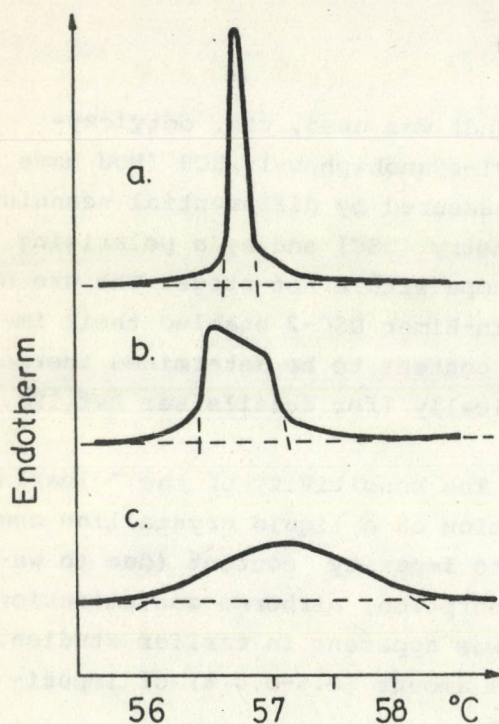


Fig. 2. The broadening of transitions: DSC traces of nematic-isotropic transition of samples (containing 60 % 8CB) of varying contamination. (a) fresh sample; (b) sample after 60 days of application; (c) excessive contamination due to prolonged absorption (sample open for weeks).

2. Sample preparation

The first procedure for thermal mapping is to cover the sample surface - in our case mostly an electronic device - with the liquid crystal. Longer thicknesses were few μm in the best cases depending on the film manufacturing method. To remove the excess amount of the melted liquid crystal from the surface of the sample an inert gas flow was used; this was necessary to protect electrical contacts on the device.

3. Experimental setup

A detailed scheme of the experimental apparatus is given in Fig. 4. A thermostable sample holder is in thermal connection with an ultra-thermostat type U-10 with a maximum stability of 0.1 K. The holder was of copper isolated thermally from the outer space but in good thermal contact with the sample housing. In many cases TO-5 or TO-18 cover cases were used because it is a common housing in electronic device technology.

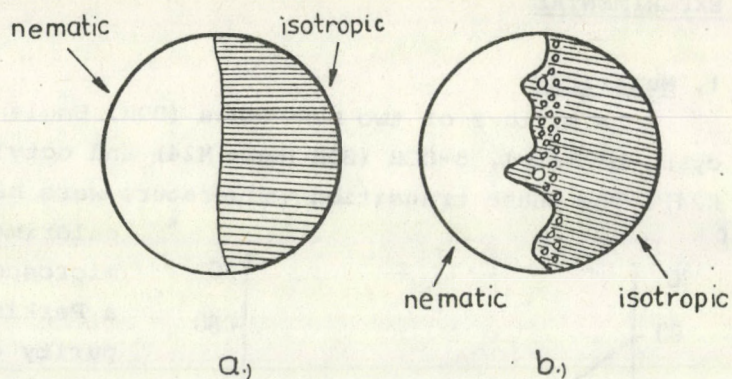


Fig. 3. Illustration of the effect of thermal gradient, on the sharpness of the boundary (T_c isothermal line): (a) ∇T is not less than 0.1 K per 1000 μm ; (b) ∇T less than 0.05-0.10 K per 1000 μm fresh sample.

(degradation) of the mixtures used was followed by DSC. After ten weeks of application the clearing point was depressed by 0.05 K only, and the transition broadened somewhat (from 0.08 K to 0.45 K, Fig. 2b). Due to intentionally "careless" application (container kept open for weeks) the clearing point depression was only 0.2 K but the width of the transition line increased by an order of magnitude.

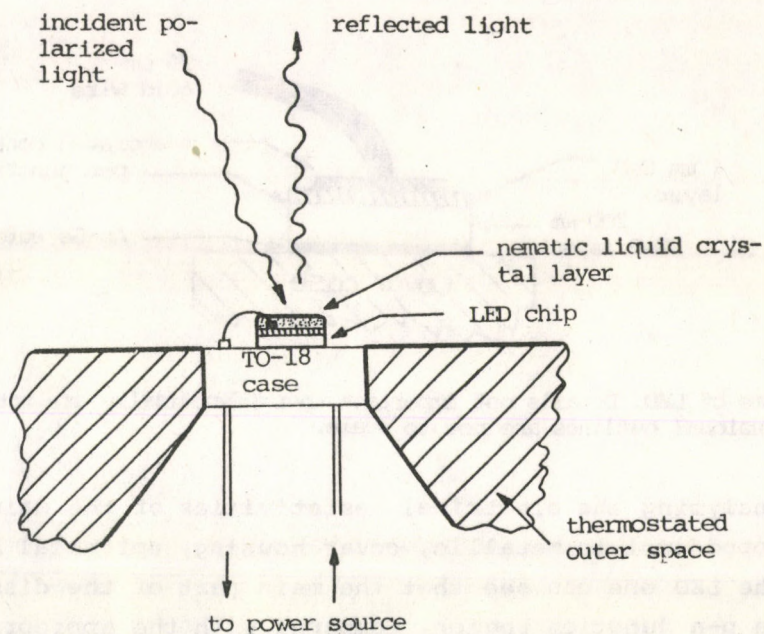


Fig. 4. Scheme of measuring arrangement for microthermography of operating electronic devices (LEDs).

For easy and good quality observation of the microcircuits we used a Carl Zeiss Jena "Amplival pol-u" type microscope in reflection mode with an "mf-matic" microphotographic research accessory. To eliminate possible heating effects of the sample we utilized heat filters (Carl-Zeiss, Jena type KG-2 colour glass). Magnification was up to 200. With crossed polarizer and analyser, we could easily distinguish the different liquid crystal phases.

(The thermodynamical problems related to the measured value of the temperature, the thermal resolution of the method, and the real temperature on the surface of the sample will be discussed in detail in the Appendix.)

4. An experimental example: thermal mapping of a light emitting diode (LED)

In our measurements we tried to demonstrate the usefulness of our method by the experiments described below. We used for thermal mapping an approximately $400\ \mu\text{m} \times 400\ \mu\text{m}$ chip of a commonly manufactured LED with an octagonal active area whose parallel sides were at a distance of $300\ \mu\text{m}$. To introduce current from the front-side we utilized two pairs of parallel vacuum-evaporated contact strips perpendicular to each other. At the crossing of the contacts a square-shaped evaporated contact serves for connection to a $25\ \mu\text{m}$ diameter gold wire with thermocompression technique. The chip itself contains a p-n junction on a GaP substrate. The dimensions and constructions can be seen in Fig. 5. A layer of GaP several μm in thickness was deposited over the heat creating p-n junction. (For a detailed analysis of the physics and technology of LEDs see for example, Ref. [11].)

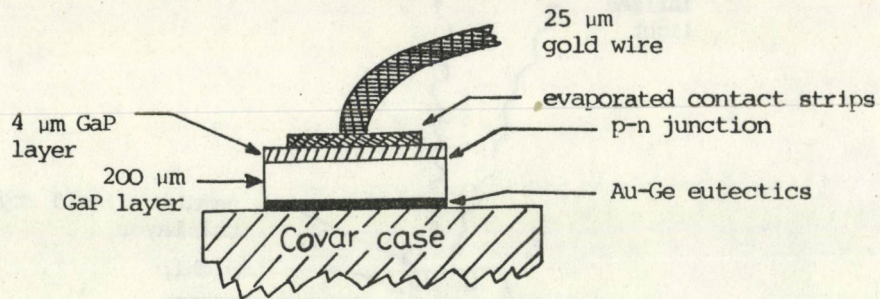


Fig. 5. Scheme of LED. Details not important thermodynamically are not represented. Dimensional outlines are not to scale.

In analysing the electrical resistivities of the main elements (i.e. substrate doped just to metallic, covar housing, epitaxial layers, gold contacts) of the LED one can see that the main part of the dissipated energy rises in the p-n junction region. Compared with the appropriate thermal conductivities this enables us to estimate the difference in temperature between the junction and the surface. The detailed analysis in the Appendix shows that the difference in temperature is much less than 0.01 K. Thus, the liquid crystals layer on the surface of the sample gives us the possibility to measure the p-n junction temperature. (Limitations of these statements are discussed in the Appendix.)

As mentioned above, the surface can be coated with a liquid crystal layer of about 10 μm thickness. With the mixture of the K24-M24 nematogenes (40 % or 60 % mole per cent) we could obtain a map of the LED surface temperature in the following way:

- 1) The sample was placed in the thermostated sample holder and its surface was coated with the mixed nematogenes. The excess of the liquid crystal was removed. The LED power supply at the desired operating level was switched on. The starting temperature of the thermostat was that at which the liquid crystal transformed to isotropic liquid at the boundary of the operating area. On subsequently lowering the temperature we could observe the transition (isothermal) lines coming closer to the centre of the LED. (In this special case it was the hottest point of the surface.) The measurements could be evaluated after subtracting the temperature of the thermostat from that of the transition temperature of the mixture. After making a set of photographs corresponding to the appropriate isothermals we could get the exact "warming map" of the microcircuit at a given electrical driving power as a parameter. This is illustrated in Fig. 6, which is a photomicrograph of a LED-chip with a well-observable phase transition trajectory. For the sake of clarity only one isothermal line can be seen. Figure 7 gives the complete map of the same sample in the temperature range from 31.5-32.5°C with a thermal resolution of

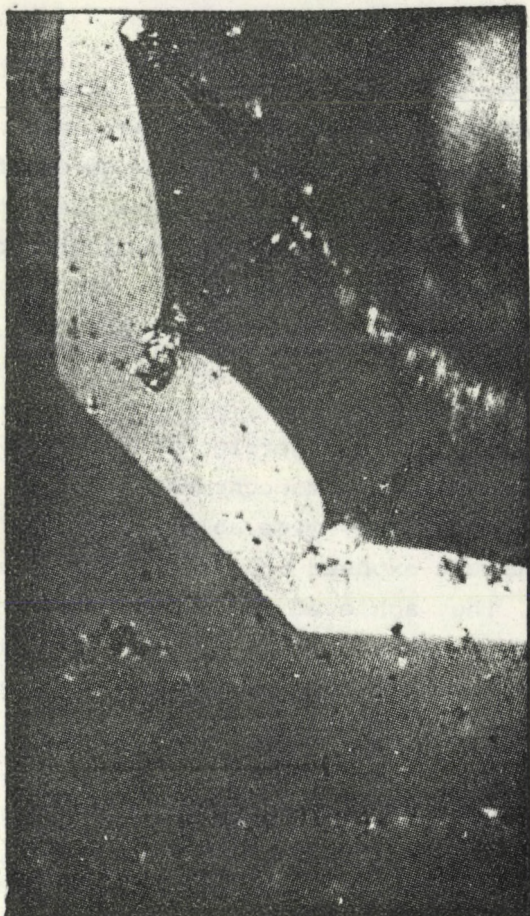


Fig. 6. Original photomicrograph of part of LED with octagonal dissipating area. The isothermal line corresponding to 31.9 K is the boundary of the nematic-isotropic regions. Using polarized incident light beam the isotropic region is the dark one. The evaporated Au-contacts can also be seen. Due to the higher current density near the contacts the surface is at higher temperature there.

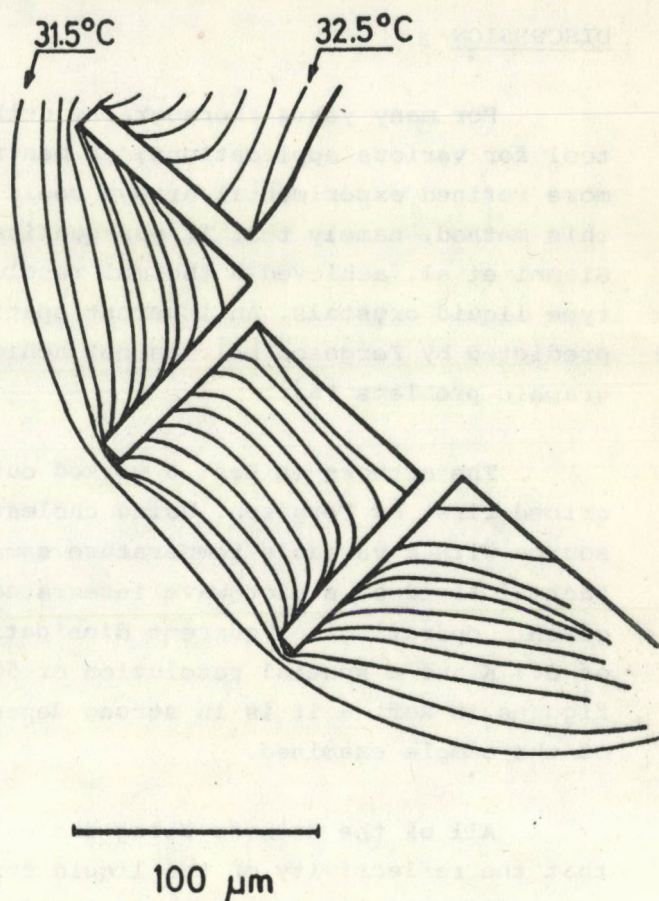


Fig. 7. Complete temperature map of the same part of LED as shown in Fig. 6 constructed from eleven similar photographs. For the sake of clarity only the outermost and innermost isothermals are marked with their temperature values. The temperature difference between two consecutive lines is 0.1 K.

0.1 K. The widths of the isothermal lines were uniformly about 2-4 μm , as can be seen on the original photograph.

2) There is a possibility for a quick visual proof, too. By changing the driving electrical power on the device one can change the surface "warming map" to higher levels. Thus, the isothermals corresponding to the transition temperature of a given liquid crystal "move" to the outer - cooler - region of the microcircuit. This gives an approximative method for the thermal mapping (approximative, because the different isothermals are related to different operating levels and so to different "warming maps"). The method is advantageous because it is simple and rapid.

DISCUSSION

For many years thermography utilizing cholesterogenes was a unique tool for various applications, as mentioned in the Introduction. But even more refined experimental arrays could not solve the fundamental problem of this method, namely that it was qualitative rather than quantitative. Recently, Gianni et al. achieved a thermal resolution of about 0.1 K with cholesteric type liquid crystals. An inherent spatial resolution of about 40 lines/mm predicted by Ferguson [4] was not achieved because of optical and photographic problems [6].

The authors in Ref. 6 worked out a more refined version of that described first by Ferguson. Using cholesterogenes and a monochromatic light source with a variable temperature sample holder they were able to map a thermal field of a microwave integrated circuit exposed on its surface to a given operating current dissipation. They achieved a thermal resolution of 0.1 K and a spatial resolution of 50 μm . However, as can be seen from the figures in Ref. 6 it is in strong dependence on the surface thermal gradient of the sample examined.

All of the methods using cholesterogenes are based on the property that the reflectivity of the liquid crystal is a function of the wavelength (i.e. its colour), it is thus selective and depends on the local temperature. But this dependence is a relatively slowly varying function of the surface coordinates. By this means, the places on the photographs with identical colour representing an isothermal line create a relatively extensive area even if the most refined optical methods are used. In view of this, the evaluating process is also not a simple one.

On the other hand, the method proposed here developed for thermal mapping of very little samples (in the 100 μm range) with very slowly varying surface thermal gradients uses nematic liquid crystals. (The limitation of the method in the case of point-like thermal sources, localized in some depth from the device surface, is discussed in the Appendix). These nematogenes were developed for applications in displays, they are relatively cheap and easily available materials. The sample surface can be coated with them without any preparation with other materials (for instance black paints) to make the isothermals visible. The use of a thermostatic system to ensure well-defined conditions for the sample measured makes our measurements really controllable. (It should be noted that the dynamical method described in Ref. 6 is also often suitable for measurements with high thermal accuracy depending on other thermodynamical parameters of the system.) The uniquely thin over-all uniform and easy observable phase transition of the nematogenes (often marked

as "clearing point") makes the method applicable not only in investigations for device failures but makes it suitable for use in really exact thermal mapping as shown in the accompanying figures. Moreover, the literature [12] on the degradation of LEDs predicts the important role of thermally activated processes. Thus real physical motivation is given to the examinations in this direction. Results in this field are due to be published elsewhere.

APPENDIX

In our measurements we could see that in most cases the surface temperature vs surface coordinates function of an LED is a slowly varying one. We could use the well-known method of thermal resistivities to calculate temperature differences between the surface and the p-n junction. From the experimental point-of-view it is negligible (less than 0.01 K). This is not the case, however, if point-like heat sources exist. We calculated theoretically the resolution of our method if heat sources of such a type are included.

In our case one component of the heat source (e.g. a p-n junction) is not exactly on the semiconductor surface but rather at some depth from it. The other component is the evaporated contact itself. Thus the temperature reaches its maximum value in the bulk, at a given distance from the surface while the described method measures surface temperatures only. The surface temperature distribution is a finite resolution image of the deep-distribution with different maximum temperature values. Now the questions arise:

- (i) What is the error, i.e. the temperature difference, between the exact temperature maximum and the measured one?
- (ii) To what extent is the spatial resolution limited by the fact that the dissipating sources are below the surface?

Model for discussion. Let us investigate the steady-state temperature distribution of the sample. This is given by the stationary heat-conduction equation [13]

$$\nabla^2 T = 0 \quad (1)$$

For the case of a unit point-source the solution of (1) is given by

$$T(r) = \frac{1}{4\pi\kappa} \frac{1}{r} \quad (2)$$

where κ is the thermal conductivity of the medium and r is the distance from the source.

The neighbourhood of the semiconductor surface is a two-region structure: one region is the semiconductor itself, the other is the air above it. The thermal conductivity of the air is $\kappa = 0.024 \text{ W/mK}$. This is four orders of magnitude smaller than that of the semiconductors (e.g. 155 W/mK for silicon). Thus, the thermal conductivity of the air can be completely neglected. Radiation is also negligible and air convection is prevented during the test. The heat propagates only in the semiconductor material so we can use the semi-infinite medium approximation. In this approximation the volume temperature distribution is given from (2) by a convolution-type integral

$$T(x, y, z) = \frac{1}{4\pi\kappa} \sum_{i=0}^1 \frac{p(\xi, \eta)}{\sqrt{(x-\xi)^2 + (y-\eta)^2 + [z+(2i-1)d]^2}} d\xi d\eta \quad (3)$$

where $p(\xi, \eta)$ is the two-dimensional dissipation density at depth d from the surface.

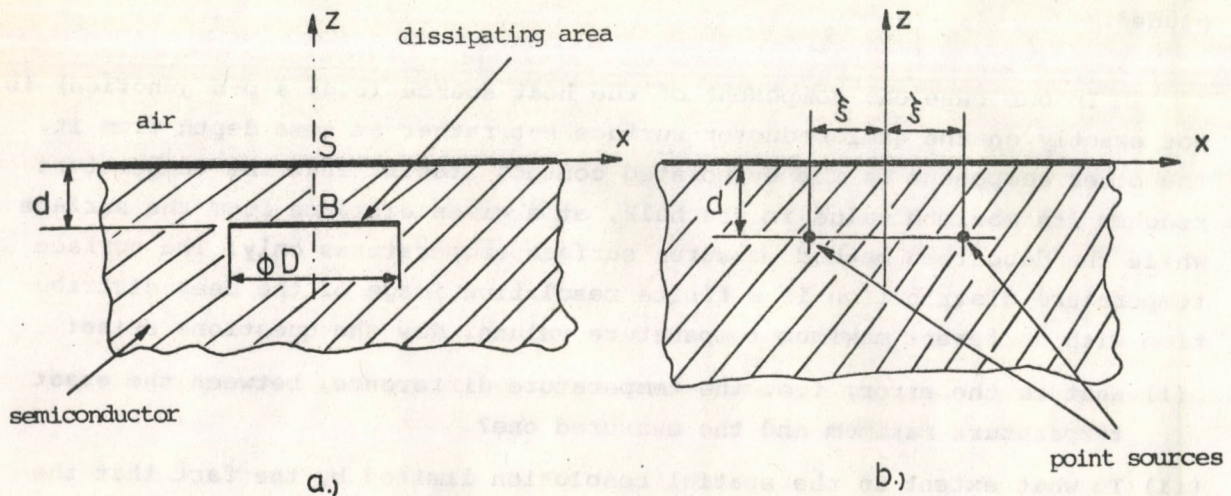


Fig. 8. Explanatory illustrations for calculations of the error and resolution of the liquid crystal thermographical method used for multilayer electronic devices.
 a) Semiconductor bulk containing a circular dissipating area with diameter D at depth d from the surface. The x axis is at the sample surface. Point B, D is in the centre of the circular area, point S is above it at the sample surface.
 b) Two point-like heat sources in the bulk of the semiconductor at depth d from its surface. The points are at a distance of 2ξ from each other.

Error of measurements of maximum temperature. For the case of a circular dissipating area of diameter D (Fig. 8a) and uniform dissipation density p , equation (3) gives the maximum bulk temperature as

$$T_B = \frac{p}{2\kappa} \left(\frac{D}{2} + \sqrt{\left(\frac{D}{2}\right)^2 + (2d)^2} - 2d \right) \quad (4)$$

referring to the point B in Fig. 8a, the maximum surface temperature is given by

$$T_S = \frac{p}{2\kappa} \left(\sqrt{D^2 + (2d)^2} - 2d \right) \quad (5)$$

referring to point S. Thus, the error in measuring the maximum temperature is

$$\Delta T = \frac{p}{2\kappa} \left(\frac{D}{2} + \sqrt{\left(\frac{D}{2}\right)^2 + (2d)^2} - \sqrt{D^2 + (2d)^2} \right) \quad (6)$$

Let's consider as an example when the dissipation density is $p = 10^7 \text{ W/m}^2$ (his value is about the allowable maximum), $\kappa = 110 \text{ W/mK}$ (as for GaP) and $d = 4 \text{ }\mu\text{m}$. In this case the error is negligible if $D > 20 \text{ }\mu\text{m}$ and is only 0.075 C° for a dissipating are of $D = 8 \text{ }\mu\text{m}$ diameter and 0.24 C° for $D = 4 \text{ }\mu\text{m}$. Thus, the error of the measured maximum temperatures is fairly small (except for very small-size heat sources).

Limit of the resolution. Two equal point sources ('hot spots') are supposed at depth d and with a distance 2ξ between them (Fig. 8b). We consider the sources theoretically distinguishables with surface measurements if their surface temperature distribution shows two distinct maxima. The surface temperature distribution along the axis x is given by

$$T(x) = \frac{1}{2\pi\kappa} \left(\frac{1}{\sqrt{d^2 + (x-\xi)^2}} + \frac{1}{\sqrt{d^2 + (x+\xi)^2}} \right) \quad (7)$$

The investigation of this expression shows that the two points are distinguishable (in the above-defined sense) if

$$\xi > 0.7071 d \quad (8)$$

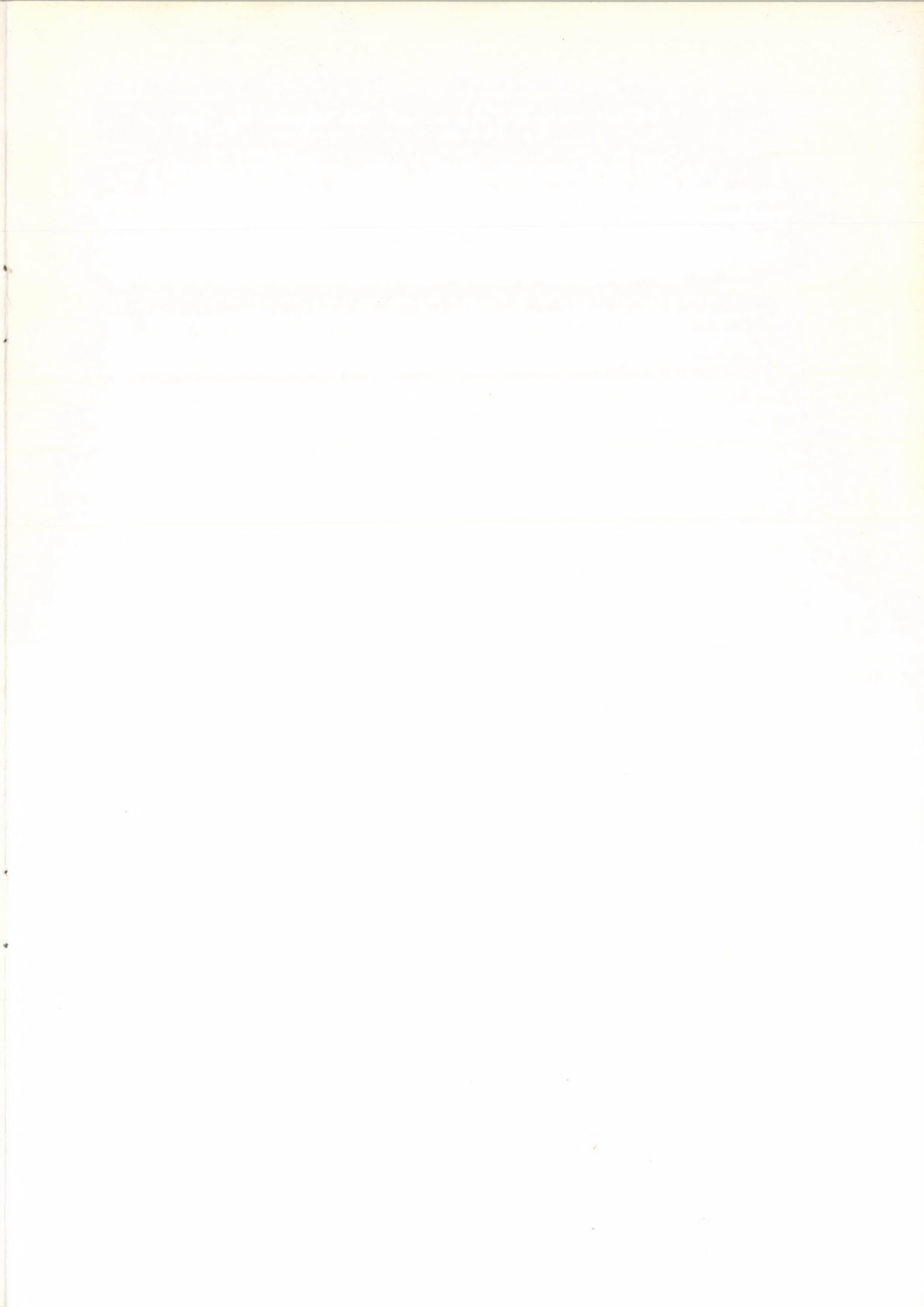
This is the theoretical limit of the resolution.

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REFERENCES

- [1] P.Carroll: Cholesteric Liquid Crystals. Their Technology and Applications (Ovum Ltd., 1973, London)
- [2] G.Meier, E.Sackmann, J.G.Grabmeier: Applications of Liquid Crystals (Springer Verlag, Berlin Heidelberg, 1975)
- [3] see for example Proc. IIIrd Conf. Liquid Crystals 1979 Budapest (Akadémiai Kiadó, Budapest; in press)
- [4] see in Appl. Optics 7 (1968) collected papers on thermography
- [5] G.V.Lukianoff: in Liquid Crystals 2, Part I, Proc. 2nd Int. Conf. in Liquid Crystals, 775 (Ed. G.H.Brown, Gordon and Breach, N.Y.)
- [6] F.Gianni, P.Maltese, R.Sorrentino: Appl. Optics 18, 3048 (1979)
- [7] J.C.Sethares, W.A.Sethares: in Proc. of the IEEE Int. Symp. on Circuits and Systems (IEEE, N.Y., 1978)
- [8] G.W. Gray: Liquid Crystals and Plastic Crystals, Vol. I, p. 327 (Ed. G.W. Gray and P.A. Winsor, Ellis Horwood Ltd, Chichester)
- [9] L. Siklós, J. Szabon: Proc. IIIrd Conf. Liquid Cryst., 1979, Budapest (in press)
- [10] J.Szabon, L.Bata, K.Pintér: KFKI-78-22 (1978)
- [11] Proc. of the Int. Autumn School on Semicond. Optoelectronics. (Semicond. sources of el. magn. radiation) Ed. by Marian A. Herman Warszawa, Polish Sci. Publ., 1976
- [12] Gy.Ferenczy: Internal Report MTA MFKI (1979)
- [13] H.S.Carslaw and J.C.Jaeger: Conduction of Heat in Solids (Oxford University Press, Oxford, England, 1959)





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Felelős kiadó: Krén Emil
Szakmai lektor: Bata Lajos
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