UDK 621.3:(53+54+621+66), ISSN0352-9045 Informacije MIDEM 25(1995)4, Ljubljana

THERMAL AND ELECTRICAL OPERATION AND MALFUNCTION OF ELECTRONICS DETECTED AND IMAGED BY MEANS OF LOW COST LIQUID CRYSTAL SENSING

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INVITED PAPER
23rd International Conference on Microelectronics, MIEL'95
31st Symposium on Devices and Materials, SD'95
September 27.-September 29., 1995, Terme Čatež, Slovenia

Key words: microelectronic components, malfunction detection, electronic circuits, electrical operation, thermal imaging, thermal loses, thermal properties, thermal images, nematic LC, nematic liquid crystals, malfunction location, measuring techniques, fine resolution, high sensitivity, resolution <1μm, polarized light, hot spots, precise temperature measurement, faulty operation tracing, hot spot location, thermal profiling, ULSI, Ultra Large Scale Integration, hybrid circuits, circuits boards

Abstract: Complex microelectronics devices of today have fine geometries, giving rise to the challenge of requiring equally fine resolution and high sensitivity measurement techniques in order to characterise their operation and to locate and help diagnose malfunction. A dual technique ideally suited to such measurement combines the high sensitivity field response and the precise isotropic transition temperature of nematic liquid crystals as invented by the author more than two decades ago. Nematic liquid crystals respond to changes in electric fields by causing brightness contrasts with a line definition of 1 micron, when viewed with polarised light. When heated, nematogens also undergo a transition from optical birefringence to isotropy at a temperature reproducible to 0.2°C also with a spatial resolution of 1 micron. A number of original analyses are illustrated, such as the failure site of a relay driver integrated circuit diagnosed by locating the consistent occurrence of a hot spot on just one branch of the dual emitter output transistor. The failure of multiple emitter power transistors was traced to the faulty operation of one of the branches of the transistor. Precise temperature measurement and characterisation of thin-film nichrome resistors and location of hot spots due to laser trimming of thick-film resistors is readily accomplished. Thus, the high-resolution capability of the liquid crystal technique for functional observation and thermal profiling has benefited the full raft of microelectronics components ranging from ULSI through to hybrid circuits and circuit boards.

Uporaba cenenih tekočih kristalov za opazovanje in odkrivanje napak delovanja elektronskih komponent in vezij

Ključne besede: deli sestavni mikroelektronski, detekcija delovanja slabega, vezja elektronska, delovanje električno, upodabljanje termično, izgube termične, lastnosti termične, slike termične, LC kristali tekoči nematični, lociranje delovanja slabega, tehnike merilne, ločljivost fina, občutljivost velika, ločljivost < 1μm, svetloba polarizirana, mesta vroča, merjenje temperature precizno, sledenje delovanja napačnega, lociranje mest vročih, profiliranje termično, ULSI integracija ultra visoke stopnje, vezja hibridna, vezja tiskana

Povzetek: Današnje kompleksne mikroelektronske komponente odlikujejo izredno majhne geometrijske strukture, ki na drugi strani zahtevajo enako fine merilne tehnike z visoko ločljivostjo in občutljivostjo, s katerimi vrednotimo delovanje teh komponent, oz. odkrivamo in diagnosticiramo njihove odpovedi. Tehnika, ki jo je izumil sam avtor pred dvema desetletjema, in je idealna za izvajanje opisanih meritev, združuje visoko občutljivost odziva in natančno temperaturo izotropnega prehoda nematičnih tekočih kristalov. Nematični tekoči kristali reagirajo na spremembo v jakosti električnega polja s spremembo v svetlobnem kontrastu s prostorsko ločljivostjo 1 μm, če jih opazujemo s polarizirano svetlobo. Ravno tako nematogeni, če jih grejemo, spremenijo stanje iz optične dvolomnosti v izotropno pri temperaturi, ki je ponovljiva do 0.2°C in prostorski ločljivosti do 1μm. V prispevku podajamo vrsto originalnih analiz s to metodo, kot npr. odpoved integriranega krmilnika relejev, kjer smo kot vzrok odpovedi odkrili vroče mesto le na enem kraku izhodnega tranzistorja z dvojnim emiterjem. Nadalje smo podobno ugotovili, da leži vzrok odpovedi močnostnega tranzistorja z večimi emiterji v odpovedi le ene njegove veje. Sledijo opisi natančnih meritev temperature in karakterizacija tankoplastnih NiCr uporov ter odkritja vročih mest zaradi laserskega doravnavanja debeloplastnih uporov. Tehnika uporabe tekočih kristalov je izredno občutljiva, cenena in primerna za opazovanje delovanja in odkrivanje napak raznovrstnih elektronskih komponent od VLSI preko hibridnih do tiskanih vezij.

1. INTRODUCTION

The electrical operation and temperature distributions in microelectronics components are clear indicators of their performance and reliability. However, such detail within a microcircuit is rarely uniform, instead being distributed according to the microscopic dimensions of the fields subtended at the surface and the power dissipation and heat conduction paths. Therefore techniques have been sought to observe electrical operation and to measure temperatures and thermal profiles on a microscopic scale.

Amongst the more popular techniques for observing microcircuit operation is the use of the scanning electron microscope (SEM) with the electron beam as the electrical probe. This provides very versatile capability and also enables prototype testing of integrated circuits (ICs) /1/. However, it does require major investment in such equipment and does require the component to be operated in vacuum and also subjects the component to high energy electrons which can alter the local behaviour of the circuit. Therefore a complementary technique which could be used in conjunction with existing laboratory microscopes and did not involve evacuation or high energy bombardment was desirable.

One of the early innovations for high resolution temperature measurement was the infrared micro-radiometer, which measures the radiation emitted from microscopic areas /2/. In principle the technique has a spatial resolution down to 8 μm and a temperature sensitivity of 0.5°C. In practice the technique rarely performs to its limits and suffers the drawback of needing considerable calibration and computation to translate the measured radiation into temperature.

In order to meet both objectives, Liquid crystals were examined following reports of the use of nematogens for electrically controlled imaging and cholesterogens to measure surface temperatures. Cholesterogens /3,4/ were soon abandoned because the technique was found to have a poor spatial resolution (>20 μm) and required the application of a non-reflecting coating which impaired the microscopic temperature profiles. Instead, an alternative property of nematic liquid crystals (nematogens) was uncovered and has been successfully exploited into a technique /5/ for the measurement of surface temperatures with a spatial resolution of better than 1 μm and sensitivity of better than 0.2°C. The TEMPCOL© (TEMPerature COntrast by Liquid-crystals) technique is briefly described in this paper which is devoted more to illustrating its application to a range of microelectronics components. During this work, it was also discovered that the identical experimental set-up was effective also in revealing the electrical operation at the surface of the microcircuit, which has therefore been developed into the VOCOL© (VOltage COntrast by Liquid-crystals) technique /6,7/, also with a spatial resolution of 1 μm.

2. THE TECHNIQUES

In its liquid state, a nematogen is birefringent at temperatures up to a well defined critical temperature *(Ti)* called its "Isotropic Point," above which it is isotropic. Thus, plane-polarised light is doubly refracted when transmitted through a nematogen below *Ti*, but is unaltered by a nematogen above *Ti*. In the application of the techniques to microcircuits, a metallurgical microscope is employed in the experimental arrangement shown in Figure 1. A planar component coated with a thin layer (~5 μm) of liquid crystal is illuminated with vertically-incident plane-polarised light and viewed through a "crossed" analyser. In the VOCOL© technique dynamic electrical operation of the circuit is then observable as locally varying microscopic regions of brightness. The

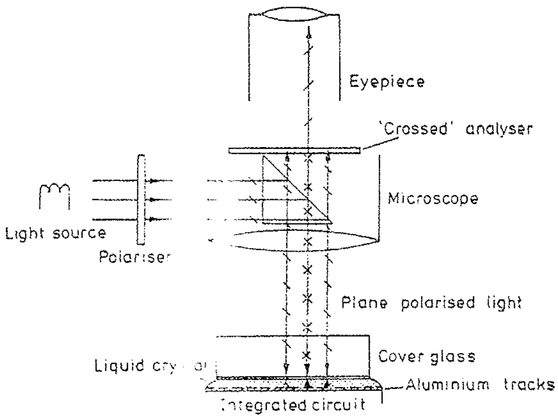

Fig. 1 : Schematic of experimental arrangement for temperature and voltage contrast

sequence of photomicrographs Figs 2a to 2d illustrate the increasing brightness associated with the positive electrodes. Such contrasts are also observable on real complex ICs, again the brightness being associated with the positive electrode according to the analysis in Reference 7. However, because the observations are of dynamic changes, photomicrographs are not convincing representations of the observed phenomena, and instead the observations have to be made in real time on a video monitor /6/.The technique has been copied and successfully exploited by many other researchers, (e.g. /8/).

In the TEMPCOL© technique, for temperature measurement and profiling, regions of the component at temperatures below Ti remain visible because one of the components of the doubly-refracted light is transmitted through the analyser; while regions above Ti appear dark because light is absorbed by the analyser. The boundaries between dark and light regions are then isotherms precisely at Ti, which has been found to be reproducible to within 0.2°C, whilst the spatial resolution has been determined to be better than 1 μm /9/. The high resolution capability is illustrated by the precise boundaries of the 5 μm diameter hot spot example (Figure 3), produced by dissipation in a thin-film nichrome resistor. In order to measure temperatures below Ti, for a particular dissipation, the component ambient temperature (Ta) is increased until light is extinguished in the area of interest. Then Ti - Ta is the temperature rise for that dissipation. The distribution of temperatures between Ti and Ta is obtained by raising Ta by small increments to produce a succession of isotherm boundaries corresponding to each Ti - Ta. The temperature distribution in the resistor from the earlier example was obtained in this way (Figure 4). Figure 4 also illustrates the manner in which the areas bounded by the isotherms widen as Ta is increased by 1°C and 2°C, and the corresponding effects are illustrated in Figures 5 and 6. Temperatures above the isotropic point of a particular nematogen may be measured either by cooling the ambient or by using nematogens with a higher Ti. Nematogens have been identified with isotropic points in the range 25°C to 300°C.

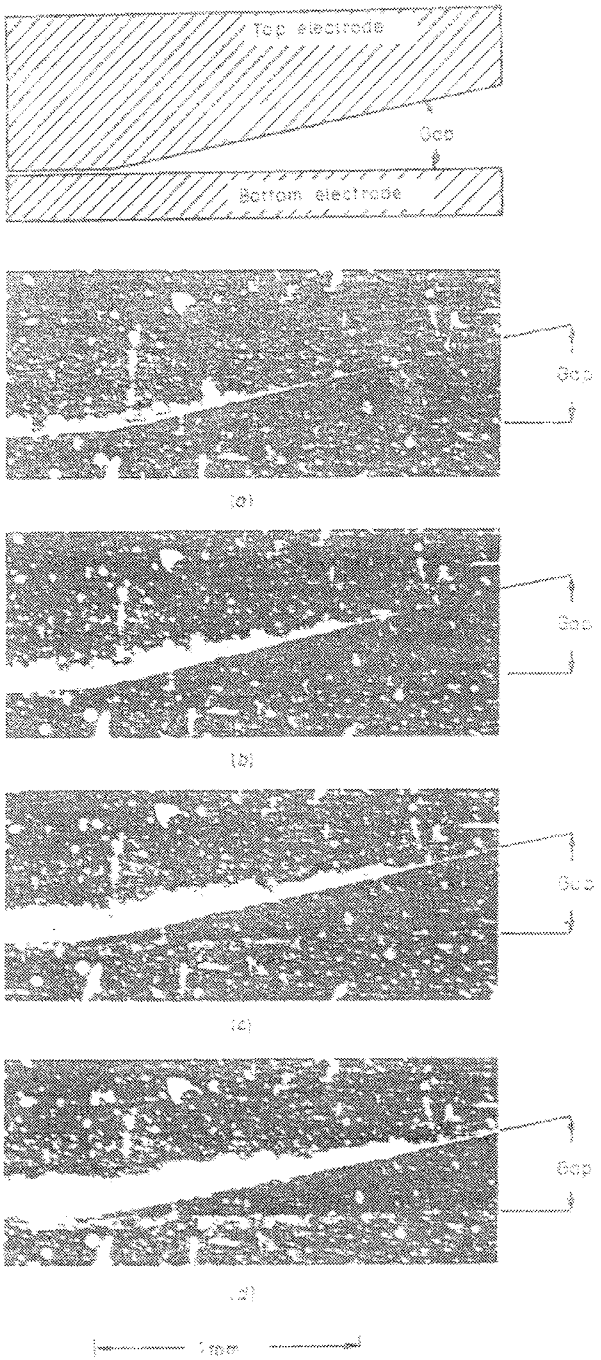

Fig. 2: *Brightness Contrasts in a Test Pattern for Positive Potentials Applied to the Top Electrode: (a) 7V, (b) 8V, (c) 9V, (d) 10V*

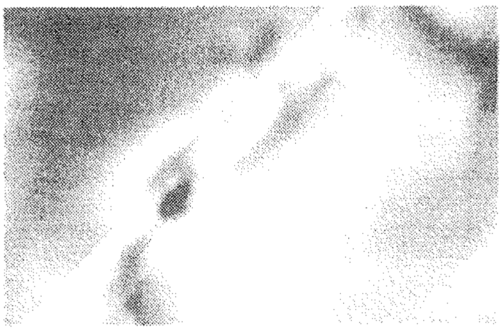

Fig. 3. Hot Spot on Nichrome Resistor (10µm wide)

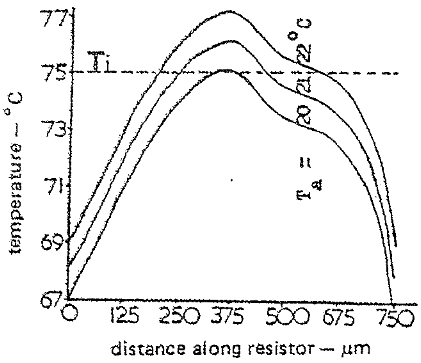

Fig. 4: *Temperature Distribution Along Resistor of Figure 3 for Successively Increased Ambient Temperatures*

Fig. 5: *Isothermal Boundaries of Figure 3 Extended by Raising Ambient by 1°C*

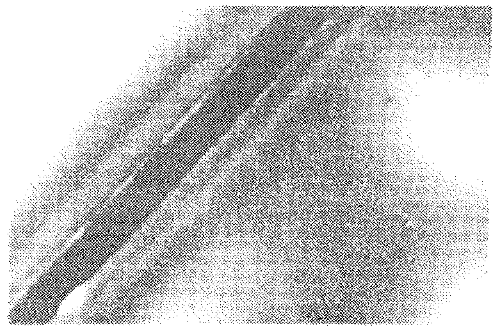

Fig. 6: *Isothermal Boundaries of Figure 3 Extended by Raising Ambient by 2°C*

3. APPLICATIONS

3.1. Monolithic Semiconductor Components

The technique is especially suited to monolithic microcircuits and transistors, where the high resolution is exploited. The following examples have been chosen to illustrate the obvious benefits of the immediate visual information obtained.

The first example shows the operation of an interdigitated transistor, clearly revealing, in Figure 7, the satisfactorily symmetrical distribution of temperature about the centre of one segment. The outer elements just reaching Ti are clearly distinguishable. Figure 8 shows that one entire segment of the transistor was malfunctioning requiring excessive dissipation in the other three segments to get the fourth up to operating temperatures.

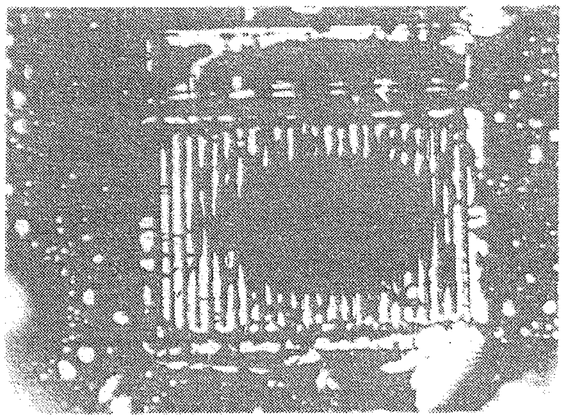

Fig. 7: Temperature of One Branch of an Interdigitated Power Transistor

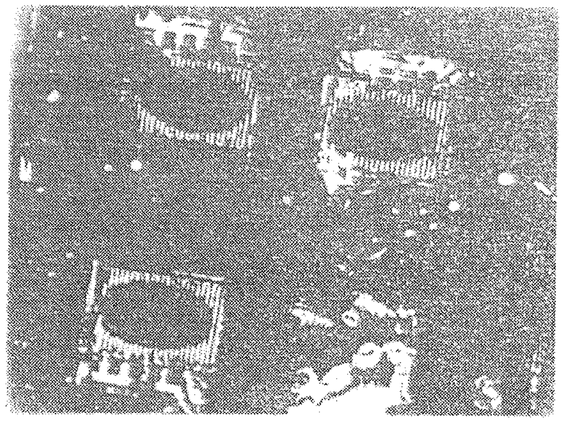

Fig. 8: Malfunction Revealed in One Segment of the Power Transistor

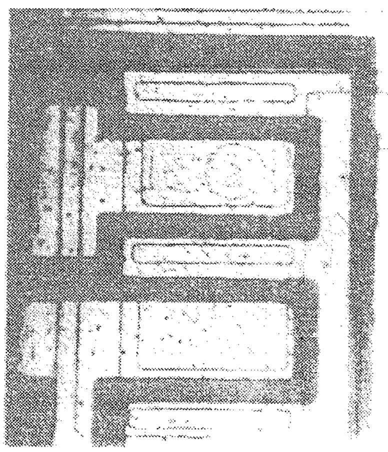

Fig. 9: Photomicrograph of Output Transistor of Relay-Driver IC

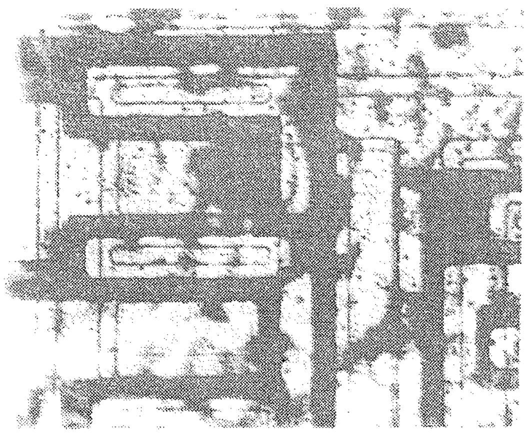

Fig. 10: Hot Spot at One of the Dual Elements of the Output Transistor of Figure 9.

A second example is of the diagnosis of faulty relay driver transistors (Figure 9) of a type that frequently failed under transient surge conditions. Figure 10 shows the hotter operation of one of the two elements of the emitter due to persistent unbalanced operation which was found to contribute to eventual failure by thermal runaway.

3.2. Thick-Film Resistors

In support of current reliability studies of other microelectronics components, attention has also been given to thick-film resistors whose large planar areas are ideally suited to examination by the technique. The examples presented here are for resistors in arrays in various dual-in-line packages, which were used as test vehicles in the studies. In order to relate thermal ageing during stress tests to the temperatures generated within the resistors, it was necessary to refer to a common parameter such as thermal resistance (R_θ) (defined as the temperature rise per unit power dissipated). Because the measurements showed that the temperature distributions were distinctly non-uniform, and ageing is fastest in the hottest parts, thermal resistances were calculated for the hottest spots on the resistors.

Single resistors gave the most straightforward results because the hot spots occurred at the known sites of maximum dissipation. Illustrated in Figure 11 is a typical observation, that hot spots always originate at the ends of laser "plunge" cuts, the hotter spots occurring at the longer cuts. The values of hot spot thermal resistance for resistors of similar geometry were found to be confined to a small range regardless of their electrical resistivity. Typical thermal resistances were 100°C/W to 125°C/W for 2 mm x 2.2 mm resistors and 55°C/W to 65°C/W for 2 mm x 4.5 mm resistors in the range 50 ohm to 50 k.ohm. Generally, resistors located in the middle of substrates had a lower thermal resistance because of the substantial heat sink surrounding them; but significant variations of R_θ also arose because of differences in the extents of laser cuts in nominally similar resistors.

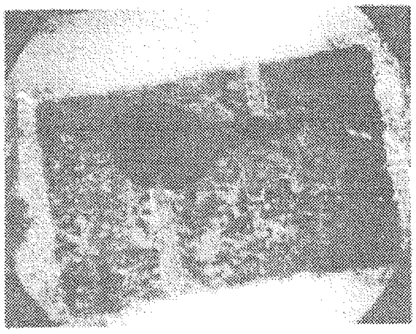

Fig. 11: Close-up of Hot Spots at the Ends of Laser Cuts of Thick Film Resistor

The technique has also been used to aid the diagnosis of faults in resistors. Low value resistors, which dramatically increased in value after exposure to voltage surges, were found to have developed hot spots at locations remote from constrictions due to trimming (Figure 12), implying that new constrictions had developed in the structures. The occurrence of cracks in the resistors, terminating at the location of the hot spots was confirmed by laboriously probing the resistors to produce equipotential contours. The contours in Figure 13 correspond to the resistor in Figure 12 (the crack looks like a laser cut).

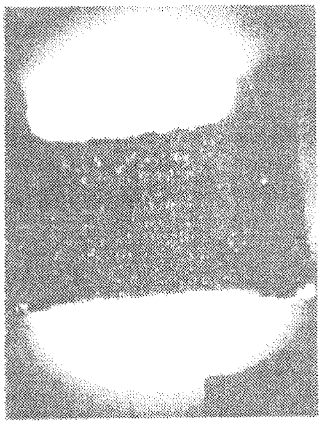

Fig. 12: Hot Spot in a Damaged Resistor

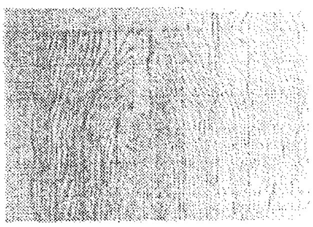

Fig. 13: Equipotential Distribution Over the Damaged Resistor

4. DISCUSSION AND CONCLUSIONS

The foregoing illustrations show that the liquid crystal technique is simple yet provides high spatial resolution, giving it distinct advantages over even the more advanced of the alternative methods of temperature measurement of microcircuits and providing a complementary alternative to the use of the SEM for observing circuit electrical function and malfunction. In principle, the method may be applied to any planar horizontal surface and has a ceiling of about 300°C. The ready application of the technique to both active and passive microelectronics components, and the obvious benefits of simultaneous visual examination of entire components have been illustrated by the examples presented.

Fine geometry ICs and also thick-film resistors have been shown to be eminently suitable components for examination by the technique, in support of characterisation, design verification versus simulation /10/ (a future paper) and reliability evaluation.

The observations of thick film resistors are consistent with heat conduction between the resistors and substrates. This was particularly notable when significantly non-uniform dissipation within a resistor array still produced a fairly uniform temperature distribution. It was only in single resistors that local dissipation played a significant part - the variation in thermal resistance due to different extents of trimming giving warning that families of resistors could age at different rates because of trimming cut variations within the design rules of some manufacturers.

The applications of the technique extend beyond the supportive role to reliability evaluation. For instance, it is clear that measurements of thermal resistance and temperature distributions can be used to estimate resistance changes associated with the temperature coefficient of resistance, and in calculating any derating adjustments that are necessary. Thus, the high-resolution capability of the liquid crystal techniques for functional observation and thermal profiling has benefited the full raft of microelectronics components ranging from ULSI through to hybrid circuits and circuit boards.

Acknowledgement

We are pleased to acknowledge the support of Temptronic Corporation in providing their ThermoSocket which has been used for precise device temperature control during this work.

We are pleased to note that Temptronic has adopted the TEMPCOL© liquid crystal technique in their product range

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Prispelo (Arrived): 29.09.1995 *Sprejeto (Accepted): 07.11.1995*