Backside Thermal Mapping Using Active Laser Probe

R. Aaron Falk
OptoMetrix, Inc.
rafalk@optomet.com

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The transition to “flip-chip” packaging has forced a renaissance in innovative failure analysis methods, usually referred to as backside failure analysis. This article describes one such technique, based on active laser probing. The technique utilizes the optical properties of the silicon substrate to produce a high-sensitivity, high-resolution thermal map of the device active area. This map can be utilized both to locate shorting defects and as a thermal management tool.

The use of thermal mapping as a tool to determine failure locations is well known to the IC failure analysis community. Typically, either a liquid crystal or temperature sensitive fluorescent material is applied to the top, active surface of the IC. Changes in the polarization of light passing through the liquid crystal reveal areas of localized heating, which indicates a potential failure site. Fluorescent Microthermal Imaging (FMI) uses the change in fluorescence of certain materials with temperature as a means to localize heat sources. Both techniques work well from the topside of an IC, but are ineffective as a backside tool due to the thick silicon substrate lying between the heat source and the heat sensing material.

We are all familiar with heat sensing via infrared radiation by holding our hands near a thermal source and “feeling the heat”. Infrared cameras are a more sophisticated methodology for this type of heat sensing and can be used from the backside to see through the silicon substrate to the active layer. Sensitivity, resolution (spatial and thermal), frame-size, and the requirement for cooled detector arrays create limitations to this approach.

Looking out over a black asphalt road on a hot summer day gives an observer no doubt as to the relative temperature of the asphalt via the shimmering heat waves rising from the road. The heat in this scene is being detected optically by its effect on the refractive index of the air above the road, which causes the image of the objects behind the road to be deflected. The refractive index of all materials, including semiconductors, is dependent on temperature. For example, Silicon has a refractive index change of $5x10^{-5}/ ^{0}C$ and GaAs has a refractive index change of $3x10^{-4}/ ^{0}C$. This second means of optical detection of temperature suggests an alternative thermal mapping approach, using laser-probing techniques and phase imaging. In particular, the form of phase imaging known as Schlieren imaging offers extraordinary sensitivity using standard laser and high-resolution CCD camera components.

Schlieren Imaging

Classical Schlieren imaging, as shown in Fig. 1, utilizes a knife-edge to partially block the optical beam on its way to the image plane. In the upper illustration in Fig. 1, Lens 1 focuses a beam of rays from the source onto a transparent object. Lens 2 re-collimates the beam, which is then re-focused onto the image plane by Lens 3. A knife-edge is placed in the focal plane of Lens 2, where an image of the source is formed, such that it partially blocks the source image. The lower illustration in Fig. 1 is identical to the upper, except that the object causes the rays passing through it to be deviated by a small angle α. This angular deviation in the object plane results in a positional shift of the source image at the knife-edge. The intensity in the image plane of the Schlieren arrangement is thus proportional to the angular deviation caused by the object.

Angular deviations can be caused by geometric variations in the object. The first historical use of a Schlieren imaging system was the Focault knife-edge test[1], which allowed observation of minute geometrical errors in the surface of optical components. A non-uniform refractive index also causes angular deviations of magnitude proportional to the spatial derivative of the refractive index. The angular sensitivity of a Schlieren system is measured in micro-radians, which translates to refractive index deviations on the order of 10^{-6}. A common use of Schlieren imaging is to detect the refractive index gradients caused by the pressure gradients in the airflow over objects in wind tunnels.

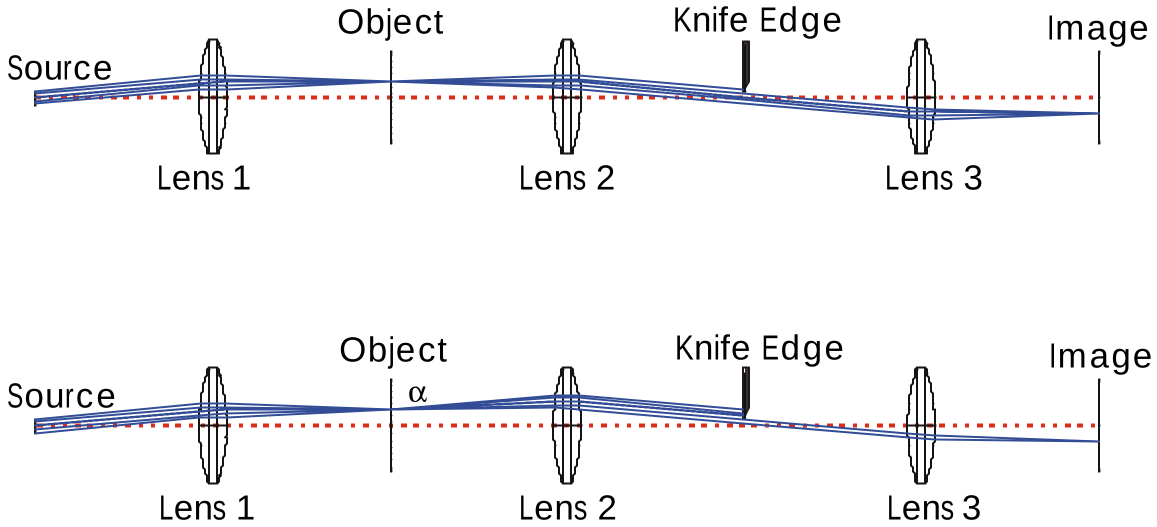

Fig. 1: *Ray traces of Schlieren imaging arrangement using ZEMAX® optical analysis software. Upper and lower traces indicate effect of deviation of the optical beam by the object.*

Fig. 1 illustrates a transmission mode Schlieren arrangement. A reflection mode arrangement, which is needed to examine an IC, is obtained by folding the transmission system about the object plane (Lens 1 and Lens 2 merge) and adding a beam splitter. The sensitivity of a Schlieren system is proportional to the source intensity, while being inversely proportional to the source size. This combination requires a high source irradiance, which suggests the high intrinsic brightness of a laser source. In addition, the source wavelength must be matched to the transmission characteristics of the test material. This requirement suggests a wavelength around 1060 nanometers for silicon (see below). A high-resolution imaging detector is also needed with a computer interface for image acquisition and processing. Digital CCD cameras offer reasonable sensitivity at the required wavelength with high-resolution imaging formats of 1024x1024 and 2048x2048 pixels coupled with 10 and 12 bit intensity resolution. Finally, although the classical Schlieren system uses a rectangular source imaged onto a knife edge filter, which produces a linear transfer function, other source and filter geometries can be used to produce a variety of other transfer functions, e.g. logarithmic.

Imagery

OptoMetrix first introduced the use of Schlieren imagery for semiconductor failure analysis as a means for diagnosing the failure mechanisms in a high-voltage GaAs switch developed by Sandia National Laboratories [1]. These switches were only on for 10-100 nanoseconds, which precluded use of many standard diagnostic techniques. Use of a pulse laser, which was synchronized to the switching event, in a Schlieren imaging apparatus allowed us to capture the transient heating caused by filamentary breakdown in the switch. Fig. 2 shows an image taken by this apparatus. The filament is observed by the Schlieren system due to the 3-4 ^{0}C temperature rise it produced in the GaAs substrate.

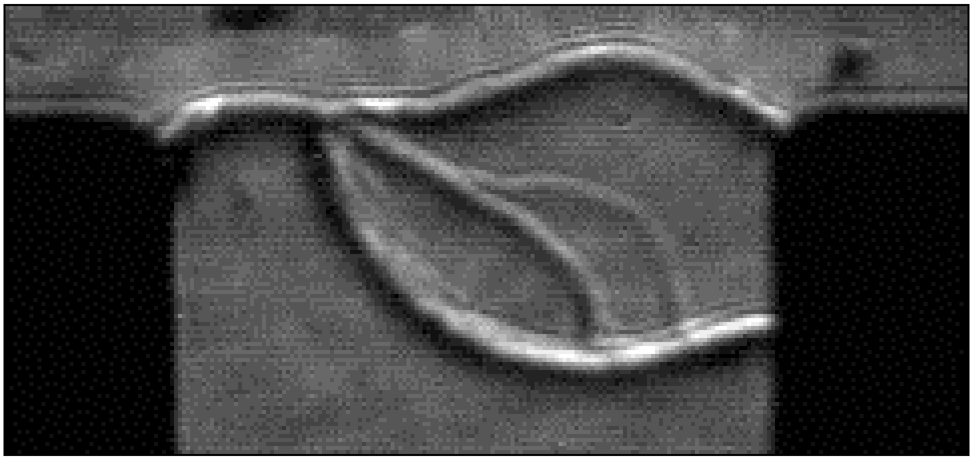

Fig. 2: *Filamentary breakdown in GaAs switch obtained using a Schlieren imaging system. The image is produced by refractive index changes in the GaAs substrate due to the 3-4 ^{0}C temperature rise caused by the transient filament.*

Although used for high power applications, the electric fields, carrier densities and temperatures in these switches were similar to those found in standard IC’s. This relationship suggested the potential for using these techniques for IC failure analysis. A program, funded by the SEMATECH Product Analysis Forum (PAF), was started in 1998 to develop a prototype Schlieren system to demonstrate this potential and determine its commercial feasibility as a backside failure analysis tool. Fig. 3 shows one of many thermal images taken using this apparatus. The limiting sensitivity of the prototype was ~ 0.05 ^{0}C for single-frame, real-time image capture, with a transverse resolution of ~ 1 μm. Images were 768x494 pixels with 8 bit intensity resolution. Thermal sensitivity was determined to be equivalent to FMI from the topside and 5 to 12 times more sensitive than detection of thermal emission with equivalent averaging. Since that first demonstration, OptoMetrix has developed a commercial version of the apparatus with thermal resolution of ~ 0.01 ^{0}C and a 10 bit, 1024x1024 image format.

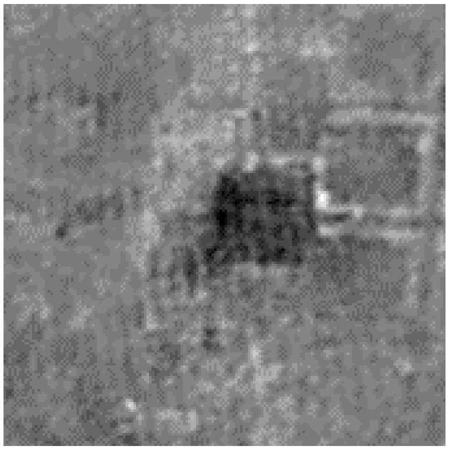

Fig. 3: *Thermal map of calibrated rectangular heating element, ~ 100x100 mm at a temperature ~ 2 ^{0}C above ambient. Darker gray indicates higher temperature.*

Device Preparation

Heavily doped silicon substrates are highly absorptive at short wavelengths due to bandgap absorption and at long wavelengths due to free carrier absorption. A window in the absorption occurs in the near infrared as shown in Fig. 4. Even within that window, the absorption of the silicon substrate can be sufficient to render imaging impossible. Thus, the most highly doped substrates must be thinned to around 200 microns [2].

In addition, the high refractive index of silicon in the near infrared, ~3.6, causes approximately 32% of the light entering the substrate to be reflected back into the detection apparatus. This glint can totally swamp out the image signal in any active imaging system and must be reduced through use of anti-reflection coatings. A single layer quarter-wave coating of a material such as silicon monoxide can reduce this reflection to less than 0.5%.

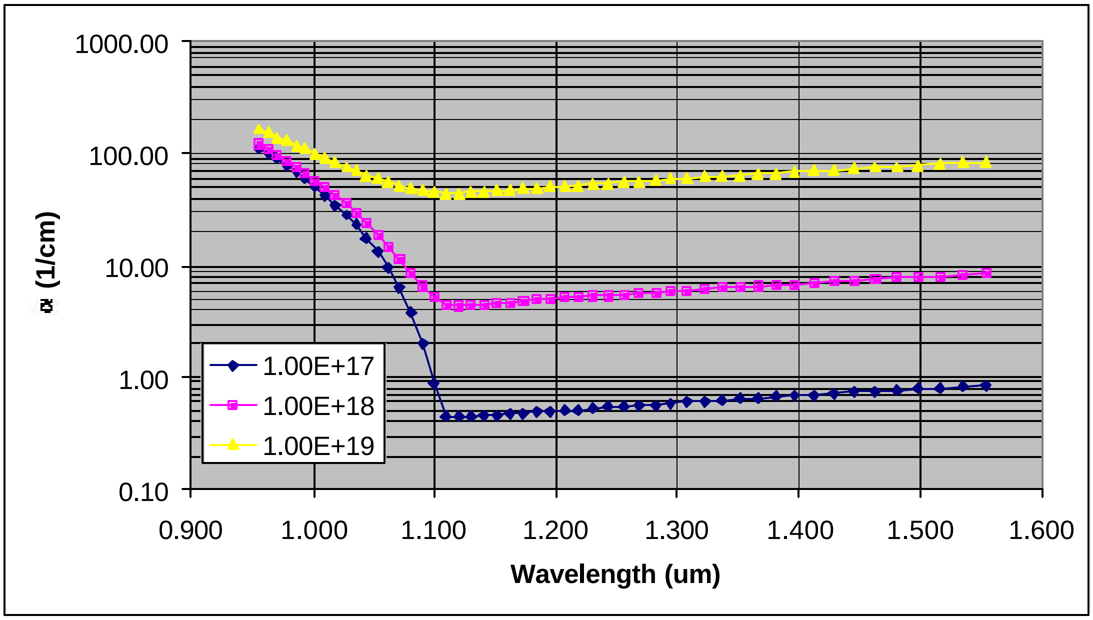

Fig. 4: *Empirical model of absorption coefficient in p doped silicon versus wavelength with p dopant density as a parameter.*

Most optically based backside techniques require thinning and application of anti-reflective coatings for optimal performance and many IC manufacturers have already developed in house systems for these processes utilizing commercially available apparatus. Outsourcing to service companies is also available.

Summary

Over the past four years, OptoMetrix has collaborated with the semiconductor community through SEMATECH PAF and others to perfect a thermal mapping system based on use of an active laser probe and Schlieren imaging. The system offers high thermal sensitivity, ~ 0.01 ^{0}C, coupled with high-resolution, < 1.0 micron, in large frame format, 1024x1024 pixels, with real time display. Short duration events can be captured through use of pulsed laser operation. Future growth areas include increased sensitivity, larger frame formats, and shorter laser pulse operation.

Footnotes

[1] Although usually seen capitalized, Schlieren is not a name. Schlieren is the German word for shadow, deriving from the shadow like character of the resultant images. L. M. Foucault is generally credited with the first use of a “Schlieren” optical system.

References

1. "Carrier Density and Thermal Images of Transient Filaments in GaAs Photoconductive Switches," R.A. Falk, F.J. Zutavern, and M.W. O'Malley, SPIE vol. 3322, pp. 243-54 (1997)

2. “Near IR Absorption in Doped Silicon - An Empirical Approach”, unpublished internal document - available on request.