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NIR Microscopy Possibilities for the Visualization of Silicon Microelectronic Structure Topology through the Substrate

O.B.Mavritskii*, A.N.Egorov, A.A.Nastulyavichus, A.A.Pechenkin, N.A.Smirnov, A.I.Chumakov

National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), Kashirskoye shosse 31, Moscow, 115409, Russia

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Abstract

Experimental setup based on visible and NIR spectral range microscope with laser port and picosecond laser is developed for silicon integrated circuit (IC) failure analysis. The possibility of visualizing the topology of the submicron technology silicon structures from the back side of the crystal through the substrate is shown. Main features of new setup are demonstrated by some results of backside focused pulsed laser beam initiated latchup effect study. The possibility of the localization of the latchup sensitive areas under focused laser irradiation is shown. NIR light emission accompanying the latchup effect is observed and analyzed. The practical aspects of NIR microscopy for failure analysis under backside laser irradiation are discussed.

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Key words: IC; microscopy; silicon substrate; picosecond laser; flip-chip.

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1. Introduction

Development of effective tools for the failure analysis of existing and newly developed electronic components is an urgent task.

Over the last decade, silicon technology has undergone significant changes such as reduced process technology and increased degree of integration, reduced power supply voltage, etc. At the same time, the methods of analysis of destructive and transient effects, leading to different type failures are permanently developed.

The destructive latchup, also known as "thyristor effect", representing the transition of the semiconductor devices into abnormal high current mode due to the mutual influence of *p-n-p* and *n-p-n* bipolar transistor structures, is of particular concern.

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* Corresponding author. Tel.: +7-495-788-56-99 ext. 8294; fax: +7-499-324-04-20.
E-mail address: oleg.mavr@gmail.com

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Such structures, essentially forming one four-layer *n-p-n-p* structure, can be either technologically provided, or parasitic. In most CMOS ICs such structures are parasitic and formed between diffusive p^+-areas and *n*-well and between diffusive *n*+-areas and the substrate [Voldman (2007)].

Latchup also occurs in modern devices with the process technology of 100 nm or less, with power supply voltages within 1 ... 2 V. This is primarily due to the fact that the decrease in specific sizes (for example, static memory cells) leads to an increase in the gain of parasitic bipolar transistor structures. Detection and localization of IC areas sensitive to this effect remains today an actual task.

Along with other devices of various complexity intended for IC failure analysis, optical microscope is traditionally used. With a microscope, one can visualize the residual effects of the occurrence of a failure by removing consequently layer by layer, because the defect area may be often hidden under metallization. It is clear that this approach requires the developed decapsulation and material removal technology [Lewis (2001)].

Since the early 1990 's a new method to determine critical electric IC modes (leading to failures) appeared, called Static Emission Microscopy (SEM). This method is based on the fact that many of the various causes of failures are similarly lead to the appearance of non-equilibrium charge carriers, which, in turn, recombine emitting a large number of photons predominantly in the near infrared (NIR) region of the spectrum.

Emission of photons in silicon devices may take place in forward or reverse biased *p-n* junction, transistor in saturation state, in the occurrence of latchup and gate rupture [Voldman (2007)]. This emission can be registered with a microscope camera sensitive in NIR range. Despite the fact that this method provides only static information, it has an undeniable advantage, since it allows to not only confirm the existence of the defect, but also visualize the place where the effect takes place prior to catastrophic failure.

In modern complex ICs, such as Field Programmable Gate Array (FPGA), the strong increase in current consumption may occur not only as a consequence of the latchup event, but also due to another functional failure such as single event upset in the IC’s configuration memory. The currents, resulting from these fundamentally different causes in one and the same IC, may be comparable in magnitude. In these cases, the correct identification of the type of failure, the examination of NIR emission and its localization may be required.

For detailed study of the possible effects causing IC failures and finding the ways to prevent them, it is very useful to have a reliable method to initiate them. Local irradiation by sharply focused pulsed laser beam gives unique opportunities in initiating a variety of single event effects (SEEs), including single event latchup (SEL) [Kastensmidt (2014)]. Choosing the proper laser wavelength allows to provide the necessary depth of penetration of radiation generating non-equilibrium charge carriers in the IC local volume in the quantity defined by the pulse energy. Varying pulse energy gives a way to determine the failure threshold while focusing of laser radiation to the point with definite coordinates on IC crystal. Iterating through the coordinates (scanning) allows to localize the most sensitive areas.

Modern integrated circuits have multilayer metallization or flip-chip packaged. Thus, visible spectrum visualization of topology elements from the active layer side is difficult or even impossible, since it is partially or completely hidden from direct observation by opaque elements of metallization or (in the flip-chip case) thick silicon substrate. Metallization also blocks passage of initiating laser beam. In this case, due to the relative transparency of silicon in middle infrared region of the spectrum, it is possible to use infrared microscopy and laser irradiation from the crystal side opposite to active layer location, so called “backside” failure analysis.

It is known that lightly doped silicon is almost transparent in the NIR spectrum (λ>1.11 μm). Heavier doping leads to increased absorption for longer wavelength due to stronger influence of free charge carriers absorption. Therefore, to visualize active layer topology through the substrate it is advisable to use spectral range greater than the specified value defined by silicon indirect bandgap.

In this case, according to results published in [Barton (1999)] and represented in Fig. 1, rough estimate shows that, even with doping level up to concentrations of about 10^{18} cm^{-1} and substrate thickness of 625 μm, light with λ~1.1 μm will be attenuated only by one order of magnitude. This allows us to hope that the intensity of light past and reflected from the metallization after repeated passage through the substrate with thickness of 300 ... 800 μm will be enough to produce the image with relatively high contrast while using microscope NIR camera with sufficient dynamic range.

Thus, to obtain a clear image of the active layer through a Si substrate, you can use the illuminator with the spectrum, having maximum close to 1.1 μm, and sensitive in this range camera.

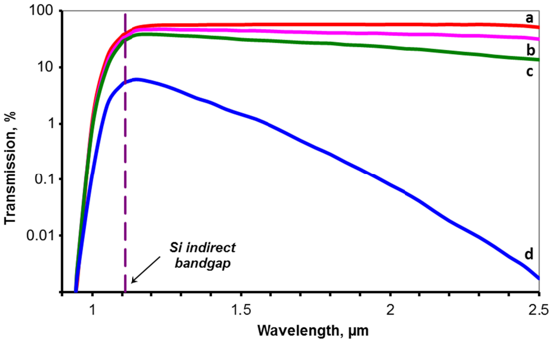

Fig. 1. IR transmission of p-doped Si (thickness 625 µm) with doping concentration $\times 10^{16}$ cm^{-3} of (a) 1.5, (b) 33, (c) 120, (d) 730 [Barton (1999)].

2. Experimental setup

Experimental setup includes industrial microscope (Fig. 2) with laser port and two observation channels (in visible and near-IR spectral range), illuminator, positioning unit and laser.

To operate simultaneously with the both visible and near-IR cameras, the wide spectral range illuminator (0.4...1.8 µm) with the heat-resistant fiber-optic bundle output is used. The lens focuses the light from the fiber-optic bundle to the front focal plane of the objective lens, thus providing telecentric shadowless illumination of the object (Kohler scheme).

Fig. 2. Microscope with two video-channels (general view).

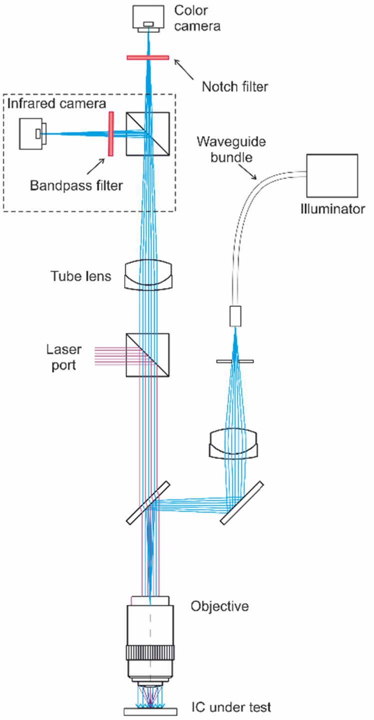

Fig. 3. Microscope optics layout.

The microscope design is based on infinity-corrected optical scheme (see Fig. 3), allowing to observe sharp image of the object at the same plane, as for the focal plane of the laser beam.

The microscope has a revolving turret for the quick change of the objectives with 5×, 20× and 100× magnification. Objective 5× can be used for the observation of the relatively large areas and getting their panoramic images, while 20× and 100× objectives – for sharp focusing of the laser beam. It is very important to choose properly the parameters of the infinity-corrected objectives. In addition to the magnification, particular attention should be paid to their numerical aperture, working distance, as well as apochromatic design in the visible and near-IR spectral range. Also, an important requirement is the resistance of optical components to high-power laser radiation. All these requirements are satisfied with the Plan APO NIR objectives, having the parameters presented in Table 1.

Table 1. Main characteristics of microscope objectives.

Magnification	Working distance, mm	Field of view*, μm	Resolution*, μm/pixel
5×	37.5	1600×1200	1.18
20×	20	400×300	0.294
100×	12	80×60	0.059

* Data presented for visual spectrum camera.

Special feature of the microscope is the usage of the wide-aperture elements in the optical path. This provides the hassle-free laser beam input and the possibility to use the cameras with sensor size up to 1”.

To observe the frontside surface of the object (from the IC active layer) the visible-range color camera is used, while for the backside research (from the IC substrate) – the near-IR range camera. The separation into two channels is performed by means of beam-splitting cube; the same cube is used to inject the laser beam in the optical path of the microscope. Special optical filters in front of cameras provide necessary spectral range selection for each channel and the protection of the cameras’ sensors from the damage by the reflected laser beam. Their specific cut-off wavelengths depend on the wavelength of the laser radiation used.

Both rough and precise focusing of the microscope is done by the vertical movement of the automated XYZ positioning unit, implementing the software-based auto-focus function along the Z-axis. The focal planes of the observation channels and the laser beam are preliminary coincided during the microscope tuning; this requires no further adjustment and simplifies focusing during the experiments.

3. Backside experiment in detail

In order to get the image of the IC active layer through the substrate it is necessary to focus on the opposite side of the substrate. To this end, after focusing to the front side of the IC crystal, the IC is further moved towards the objective lens. Tuning to the active layer in this case is much more complicated, than for frontside located structures, due to the negative influence of the front surface reflection, which disturbs the auto-focus process. However, auto-focusing in some narrower movement range still remains possible, if we preliminary move the IC towards the objective lens by the distance Δz, calculated from the substrate thickness d_s, taking into account the change of light beam divergence in silicon, which has much greater refractive index ($n=3.56$ for $\lambda=1$ μm), than for the air. Numerical calculation using Gaussian approximation of the beam propagation while focusing in silicon volume has also shown, that for spectral range of IR camera, not greater than 0.5 μm, the dispersion in silicon should not significantly affect the clarity of the obtained images.

In practice, the thickness of the substrate for the specific IC type is often unknown beforehand, and in this case one of the active layer depth position estimation methods, described in [Pechenkin (2015)], should be used, or the Δz value can be simply chosen on the basis of the similar IC type’s experience.

During the experimental setup development, special attention was paid to the selection of the spectral parameters of the microscope components. Fig. 4 presents the combination of normalized spectra of the illuminator light, IR-camera sensitivity and transmission spectrum of the additional protective filter, mounted in front of the IR-camera. The resulting spectrum of the microscope optical path is shown by the solid line. One can notice, that such spectral characteristics bring the maximum of the spectral sensitivity close to the wavelength of laser, thus allowing to simultaneously get the clear images of the active layer topology and the sharp focusing of the laser beam through the substrate (similarly to frontside geometry).

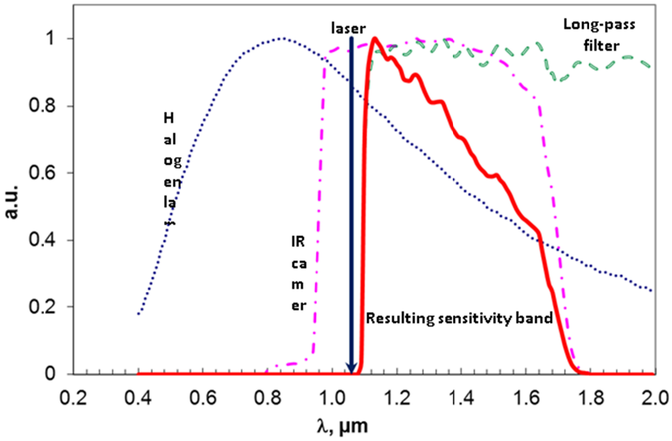

Fig. 4. Spectral characteristics of halogen illuminator, IR camera response and long-pass filter giving overall sensitivity band of NIR video channel.

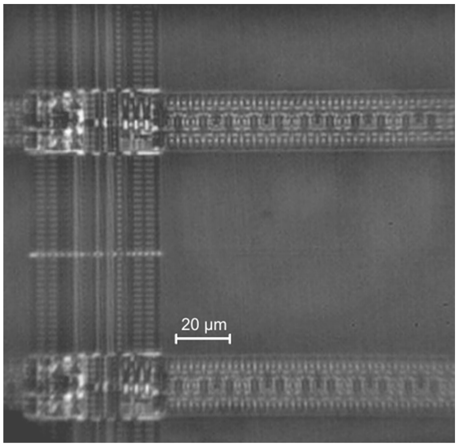

Fig. 5. Topology image of 65 nm test RAM structure, obtained through the doped silicon substrate (400 μm).

Fig. 5 represents the example image of 65 nm test RAM structure, obtained through the $2{\cdot}10^{15}$ cm^{-3} doped silicon substrate of 400 μm thickness. One can clearly see the elements with the dimensions as small as 1 μm. Such resolution is quite enough to identify unambiguously the separate elements of the IC functional blocks.

4. Static emission microscopy of latchup effects

The capabilities of the experimental setup are illustrated here by some results of SEL study in Xilinx Virtex 6 FPGA (40 nm copper CMOS process technology, flip-chip packaging), performed using the focused picosecond laser initiation (70 ps, 1.064 μm) from the back side of the 800 μm substrate. SEL was registered by the severe increase of power supply current as a result of laser pulse impact, which can be reset by temporary power supply interruption. To prevent the thermal damage of the IC structures due to the high current, the limiting of the power supply current was utilized.

SEL sensitive areas were localized using the procedure described in [Chumakov (2011)] by the consequent scanning of the whole crystal with the laser pulses of a certain energy. At the occurrence of SEL, the power supply was shortly interrupted, and the laser beam coordinates were recorded on a topological map of IC. Most sensitive areas were revealed by further rescanning with gradually decreased laser pulse energy down to the SEL threshold energy.

During the experiment, the center of IR-camera's field of view was always coincident with the focused laser beam. Fig. 6 shows the series of NIR images of one of the most sensitive IC areas when initiating SEL at the same point by a single laser pulse with a fixed energy exceeding the SEL threshold. All images were obtained at the same conditions except for the preset level of power supply current limiting. The IC's power supply current before the impact of laser was 0.2 A. On all images one can see light emission area in the form of a stripe with the length, depending on the power supply current limiting value. The length of the strip for 2.9 A current is four times greater, than for 0.36 A. Moreover, when gradually increasing the current limiting value, one can observe the stepwise increase of the strip length up to almost eight times (like LED linear scale indicator). Possible explanation of such behavior could be the significant voltage drop along the metal bus due to SEL high current propagation, which causes the connected IC elements to operate at different supply voltage (so called "rail span collapse" [Chumakov (2006)]).

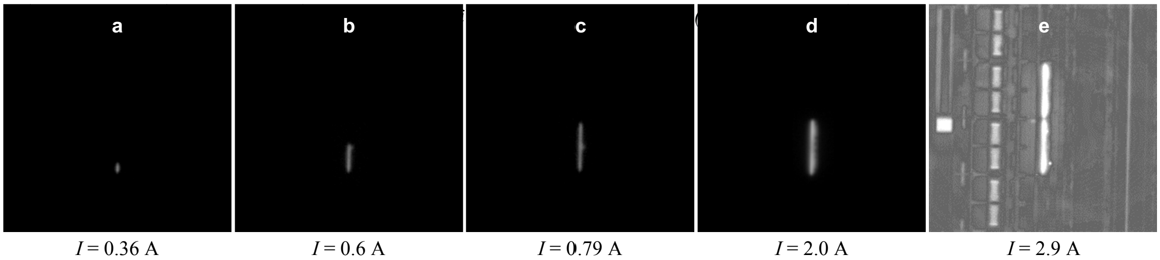

Fig. 6. SEL event light emission images, registered at various limiting levels of power supply current I. (a)-(d) – NIR illuminator is "off"; (e) – illuminator is "on".

It should be noted, that the laser beam point of incidence is located approximately 20 μm above the lower (in the Fig. 6) edge of the light strip. Such behavior can be explained by the difference in location of latchup structure and well contact(s). To exclude misinterpreting the intensive reflection from the metal layers as the light emission, the first two images were obtained with the illumination switched off, while the last one – with the illumination switched on. Indeed, if we decrease the energy of the laser pulse below SEL threshold, the light emission disappeared together with SEL. Thus, it was shown, that in this case the observed strip is caused by SEL.

5. Conclusions

The experimental setup for the failure analysis in silicon ICs was developed, including the microscope with the visible and IR observation channels and the initiating pulsed laser. The possibility of submicron topology visualization o through the substrate with up to 800 μm thickness was proved; the clear images of 1 μm sized IC elements were obtained. The possibility of application of Static Emission Microscopy method for flip-chip package ICs was demonstrated by the research of single event latchup effects caused by sharply focused picosecond laser radiation. The specific NIR light emission of thyristor effect event areas was registered through the substrate.

Acknowledgements

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