Three-dimensional nanometric sub-surface imaging of a silicon flip-chip using the two-photon optical beam induced current method


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Abstract

Two- and three-dimensional sub-surface optical beam induced current imaging of a silicon flip-chip is described and is illustrated by results corresponding to 166 nm lateral resolution and an axial performance capable of localising feature depths to around 100 nm accuracy. The experimental results are compared with theoretically modelled performance based on analytic expressions for the system point spread functions valid for high numerical apertures, and are interpreted using numerical geometric ray tracing calculations. Examples of depth-resolved feature profiling are presented and include depth cross-sections through a matrix of tungsten vias and a depth-resolved image of part of a poly-silicon wire.

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1. Introduction

The semiconductor industry is characterised by the exponential rate at which its products increase in speed, integration density and functionality, all trends that can be attributed to a steady fall in the feature sizes of integrated circuits (ICs). As feature sizes below 100 nm become routine, the international technology roadmap for semiconductors has identified a critical need for “non-destructive wafer/mask level microscopy for measuring the critical dimensions of 3D structures and defect detection” [1]. In this context, optical imaging has a role to play in IC inspection and metrology, often being used for the purposes of high resolution navigation on a prototype device prior to implementing a remedial procedure such as ion-beam milling.

Confocal laser scanning microscopy represents the current method of choice for sub-surface optical microscopy, and combined with solid immersion techniques has been shown to be capable of resolutions of 230 nm at 1064 nm [2]. In this paper we describe a complementary approach based on the optical beam induced current method (OBIC), used in a two-photon excitation mode. In this way we achieve a lateral resolutions of 166 nm and comparable resolution in the axial direction.

1.1. OBIC imaging

OBIC imaging in silicon integrated circuits was first demonstrated in the 1970s [3] and is closely related to the common electron-beam induced current (EBIC) imaging method [4] with the exception that no charge build up is associated with OBIC imaging. In the OBIC effect, optical radiation with a high photon energy greater than the bandgap is absorbed in a semiconductor sample, generating carriers. In bulk silicon the carriers will diffuse and eventually recombine through non-radiative processes. The presence of a junction in the irradiation region presents the carriers with a space-charge region whose field can sweep the carriers out to a suitable external circuit where a photocurrent can be detected [5]. When this photocurrent is mapped as a function of beam position, a topological image of the circuit can be acquired which exhibits contrast according to the electrical properties of the device.

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OBIC imaging is particularly suited to the inspection of semiconductor devices [6] due to the fact that it is a non-contact, non-destructive testing method. This created a great interest in this technique throughout the 1980s [7–11]. However, OBIC imaging cannot perform depth-resolved analysis because absorption takes place throughout the entire volume of the beam within the sample, generating carriers over a large axial range. A further drawback to this technique is the fact that the beam generates carriers throughout its irradiation volume, limiting the contrast of the image and attenuating the beam as it travels through the sample to the device layer. This is important in sub-surface imaging when one is interested in imaging a structure that is buried several hundreds of microns below the surface of the sample. Such a situation arises almost universally in modern flip-chip integrated circuits (ICs) which are designed in a manner that does not allow front-side optical access to the circuit because of the numerous metallisation layers that occupy the top side of the chip. For this reason, optical microscopy of flip-chips must be performed by backside imaging through the silicon substrate which is typically 100 μm thick. This procedure presents the contradictory requirements of achieving high bulk transmission of the illuminating wavelength, yet also sufficient absorption at the same wavelength to generate carriers at the circuit features. These two requirements involve a subtle compromise between generated signal level, illumination wavelength, image contrast and penetration depth. In silicon, these conditions are generally met through the use of a 1064 nm confocal laser scanning microscope system. Although this wavelength is close to the absorption band-edge of silicon, there is enough transmitted light to generate a substantial OBIC signal, even in devices in which the die has not been thinned.

OBIC imaging is a linear technique and therefore suffers from the same limitations in resolution and contrast as laser fluorescence microscopy, including signal saturation and limited depth-resolution. For these reasons a nonlinear variant of the technique can be used, and the following section introduces the two-photon OBIC method which we have developed for three-dimensional imaging.

### 1.2. TOBIC microscopy

Two-photon absorption is a nonlinear effect and, although hard to observe using continuous-wave (CW) laser sources can be readily demonstrated with a few milliwatts of light using femtosecond pulses from a modelocked laser. TOBIC imaging was first demonstrated by Xu [12,13] using a 1.3 μm femtosecond optical parametric oscillator, and addressed the contradictory requirements of focusing through thick substrates while maintaining sufficient absorption at the beam focus of a laser beam to produce a strong OBIC signal.

As with two-photon fluorescence microscopy, TOBIC imaging also has the ability to produce an intrinsic increase in resolution for any given wavelength. This is because the two-photon absorption effect depends on the square of the optical intensity that arrives at the focus of the beam and therefore reduces the size of the effective spot radius by a factor of $\sqrt{2}$ if a Gaussian transverse profile is assumed. In our work we make use of this fact, together with the resolution enhancing capabilities of a solid immersion lens, to achieve unprecedented optical resolutions using incident radiation with a wavelength of 1.53 μm. In a further analogy with two-photon fluorescence microscopy, we showed in previous work that the TOBIC effect can provide a means of three-dimensionally resolved imaging [14–16] because the generation of significant photocurrent only occurs within one confocal parameter of the focused spot. The axial resolution provided is similar to that obtained through confocal imaging methods in which the double-pass of the imaging system improves its axial resolution [17].

### 1.3. Solid immersion lens microscopy using TOBIC imaging

In previous work, Ippolito et al showed that a solid immersion lens (SIL) could be used to achieve a resolution of 230 nm by imaging at 1064 nm [2]. Subsequently we showed, using imaging at 1530 nm, resolutions as low as 166 nm [16,18] by implementing TOBIC microscopy using a SIL. Details of the theory of SIL imaging are given by Born and Wolf [19] and can be used to separate SIL imaging into two modalities, hemispherical (h) SIL imaging and super-SIL (s-SIL) imaging. Imaging using an h-SIL is most appropriate for structures that lie close to the surface of a sample [20], while s-SIL imaging can be configured to image at a given distance below the surface of a sample. We use the s-SIL modality because we are interested in resolving circuit features located around 100 μm below the backside surface of the silicon die. The details of the prescription used to design the correct s-SIL for imaging at a given sub-surface depth are presented in [2].

Common resolution formulae can be used to calculate the resolution expected from using s-SIL imaging. The usual expression for numerical aperture (NA) applies to SIL imaging and is $NA = snA$ where $s$ is the half-angle of the cone formed inside a material of refractive index $n$ by the converging rays at the beam focus. The maximum possible NA cannot exceed $n$ since this corresponds to the rays of the focused laser beam arriving over a cone half-angle of 90° which is difficult to achieve experimentally. Sparrow’s criterion [21] gives the smallest resolvable feature size as $0.51 / NA$ under linear imaging. In two-photon SIL imaging this becomes $0.51 / nh^2$ which implies a resolution limit of 160 nm for imaging at a free-space wavelength of 1530 nm.

We have carried out modelling of the radial point spread function (PSF) using an analytical result that is valid at high NA [22] and gives the optical field, $\psi$ measured at the observation plane as:

$$\psi(\eta) = 2 \int_0^1 A(r) \exp[i\Phi(r)]J_0(\eta r)r\,dr,$$  \hspace{1cm} (1)
where $\Phi(r)$ and $A(r)$ are the phase and amplitude profile of the light before the pupil of the focusing lens. A corresponding analytic expression for the axial point spread function is given by Sheppard and Hegedus [23] and takes the form:

$$\psi(z) = 2 \int_0^1 A(r) \exp[iu(z)r^2/2]r \, dr,$$

where

$$u(z) = \frac{8\pi z}{\lambda} \sin^2(\alpha/2).$$

Fig. 1 presents plots of the lateral (a) and axial (b) point spread functions of the light focused inside a silicon sample at NA = 3.4 which corresponds to a cone half-angle of 78°. The left side of each plot is the point spread function obtained under linear imaging (proportional to $|\psi|^2$) and the right side represents the effective PSF due to two-photon excitation (proportional to $|\psi|^4$).

Our models predict diffraction-limited resolutions, under two-photon excitation, of 168 nm (lateral) and 350 nm (axial). The agreement between the exact lateral resolution and that inferred from Sparrow’s criterion indicates that Sparrow’s criterion is a useful way of predicting the resolution achievable using TOBIC SIL imaging. The experimentally obtained value of 166 nm also agrees well with this theoretically predicted value. We have no independent measurement of the axial point spread function, however the formulae for the lateral and axial point spread functions share the same theoretical basis so we can be confident that the calculated axial resolution of 350 nm is close to that which would be observed experimentally.

### 1.3.1. Spatial calibration in three-dimensions: the optical lever effect

Sample-scanned s-SIL images are subject to an ‘optical lever’ effect in which the distance moved by the optical focus inside the sample is smaller than the physical displacement of the sample relative to the illuminating beam.

Standard results for the lateral and axial scaling factors make the assumption of paraxial rays, but this is clearly not valid under high NA conditions. In order to avoid inappropriate assumptions embedded in the standard analytical results we analyzed the axial and lateral optical lever effect in both h-SIL and s-SIL imaging by using the ray tracing software ASAP (Breault Research Organization).

Fig. 2 illustrates the analysis procedure. Rays focused by a s-SIL designed for imaging at 100 µm below the surface of a silicon die were modelled at various lateral displacements of the sample and SIL relative to the illuminating beam. We used a primary objective with a NA = 0.42 which corresponded to experiment. The optical focus was defined as the region in the sample showing the smallest lateral spread of the ray bundle, and this definition should be consistent with the experimental axial position that yields the highest two-photon signal. For a given physical displacement of the sample and SIL the corresponding optical displacement of the focus was given by the model (inset, Fig. 2). By correlating the movement of the focal position with the physical displacement of the sample and SIL we extracted a scaling factor for a range of different values of sample and SIL refractive index.

The logarithmic plots in Fig. 3 represent the lateral and axial scaling factors for an s-SIL and an h-SIL as a function of the refractive index of the SIL. For sub-surface imaging (s-SIL) the index of the SIL and the medium are chosen to be equal. Dealing first with the lateral behaviour, the slope of the s-SIL plot in Fig. 3 is exactly 2, which confirms the $n^2$ lateral scaling factor for the s-SIL, and the slope of the h-SIL plot is exactly 1, which indicates a scaling factor of $n$. In both cases this behaviour is consistent with analytic results predicted by paraxial theory.

When axial behaviour is considered the literature gives axial scaling factors of $n$ and $n^3$ for the h-SIL and s-SIL,
respectively [24]. Our modelling confirms the h-SIL result but shows an approximately $n^{3.5}$ scaling for the s-SIL which, for a silicon s-SIL, gives an optical: physical scaling factor of around 75. We have used this figure to interpret subsequent experimental results which used axial scanning to acquire a sub-surface depth-resolved image of the circuit.

2. High resolution 2D imaging in two-photon optical-beam-induced current mode

Observable two-photon absorption requires femtosecond laser illumination at a wavelength longer than the band-edge of silicon ($\sim 1.05 \mu m$), and in this work we used a femtosecond erbium-doped fiber laser, operating at 1.53 $\mu m$, to image a 0.35 $\mu m$ feature size silicon flip-chip. The laser produced pulses with a duration of around 400 fs at a repetition rate of around 30 MHz, and the average optical power at the sample was around 5 mW. This laser can be readily constructed from standard telecommunication components and its design is described in [25].

The device imaged in this work had a polished 100 $\mu m$-thick substrate and the SIL was placed on the backside of this substrate and was used in combination with a 0.42 NA objective lens. The Gaussian laser beam, full-width half-maximum (FWHM) diameter 3.3 mm, overfilled the 3 mm diameter pupil of the objective lens. After the objective lens the beam also overfilled the SIL, and a simple ray tracing analysis implied a maximum usable NA of 3.4, corresponding to the value taken in the model of the PSF discussed in Section 1. The sample and SIL were scanned using stepper motors with a minimum physical step of 100 nm which corresponded to a lateral optical step of 8.3 nm through the optical lever effect. Two-photon photocurrent generation was detected using a digital oscilloscope, and a desktop PC was used to control the scanning and to visualise the data.

The device was imaged initially using relatively coarse (800 nm optical) stepping to provide a map suitable for navigation purposes, shown in Fig. 6. The lateral resolution was evaluated by recording a higher resolution image of the area (left inset, Fig. 4). This region contained a finger of n-silicon under metal, and a resolution measurement of 166 nm was inferred from a line-scan taken across the edge of this feature which is presented in [16]. In subsequent experiments we have found it straightforward to repeatably obtain very similar resolutions at widely separated points across the sample. At such resolutions we were able to clearly resolve individual features which we believe are tungsten vias arranged in a $3 \times 3$ grid at separations of 1.25 $\mu m$. The right inset of Fig. 4 shows these vias on the design schematic for the device (circled).

3. Extension to nanometric 3D imaging

Using a peak detection procedure it is possible to exploit the focal dependence of the two-photon signal to acquire depth-resolved images that reveal the axial extent of subsurface circuit features [14,15]. The ray tracing analysis described in Section 1 provides essential information for calibrating the depth-resolved images obtained in this way using an s-SIL.

Three-dimensional profiling was performed by acquiring a set of 2D images, each one recorded at a different axial position of the sample. In the resulting data-cube, a peak detection algorithm was used to find the axial position corresponding to the maximum TOBIC signal at each lateral position in the $XY$-plane. In one experiment we profiled the area of the device containing the $3 \times 3$ grid of vias with...
The aim of determining their height. Fig. 5 shows cross-sections through these data in the X and Y directions (Fig. 4, left inset arrows), indicating that the contacts had a height of around 100 nm. The absolute contact heights, as inferred from the cross-sectional data, are consistent to ±60 nm.

In a separate profiling experiment we imaged the region indicated by the arrow in the main image of Fig. 4. This point corresponds to one end of a poly-silicon wire and the photocurrent image (Fig. 4) shows a region of low TOBIC signal. A depth-resolved image (Fig. 6) appears to reveal the presence of a hole in the centre of the feature, while the surrounding region is uniform in height to around 100 nm.

4. Conclusions

High resolution optical imaging implemented with a s-SIL has been carried out using the TOBIC effect and shows promise for resolving sub-surface features which are not accessible to inspection using electron-beam, atomic force microscopy or other high resolution inspection techniques. Resolutions in the 100–200 nm range are available in all three-dimensions and we expect that further improvements in the lateral resolution could be achieved by applying aperture engineering techniques to achieve super-resolution.

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