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High-Performance Optics for Thermal Microscopy

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We have developed a thermal microscope which has an InSb detector and optics optimized for the camera. Using this system, we evaluated maximum resolution of a 30×/numerical aperture 0.71 lens made of silicon and germanium, and achieved the cutoff frequency of around 300 line pairs/mm, which is almost a diffraction-limited performance. The thermal microscope is installed on the THEMOS-1000, a product of Hamamatsu Photonics, for thermal emission analysis.

Keywords: thermal imaging, thermal microscopy, thermal emission analysis, InSb, failure analysis, semiconductor

1. Introduction

Reliability of electronic equipment strongly depends on semiconductor devices, which are making great progress. Rapidly localizing failures and identifying their root cause in integrated circuits is thus essential to provide feedback for the design of devices and the manufacturing process. Thermal emission analysis is used in analyzing semiconductor device failures to detect short circuits or abnormal heat generation.[1] There has been a sharp rise in demand for this analysis because failures caused by semiconductor devices have been increasing as a result of their being downsized. Further, greater analytical accuracy is needed because of low voltage design.

To date liquid crystal analysis (LCA) has been widely used in these analyses.[2] The effect is used in the method that liquid crystals respond to the semiconductor surface temperature by altering the refractive and reflective properties as the temperature changes. However, spatial resolution strongly depends on an operator's skill in applying the liquid crystal to the semiconductor surface, which is limited to approximately 10–20 μm. Further, handling liquid crystal is not good for human health, and is not ecological. Thermal microscopy, using PtSi, etc. as a focal plane array detector, has also been used for analysis. This method is advantageous for its ease of operation without any surface preparation, however, as a result of its low sensitivity, a device to be analyzed must be heated up by a hot chuck.

Recently, an infrared camera, with the wavelength range of 3–5 μm, has been developed with dramatically higher sensitivity than before using InSb as a focal plane array detector.[3] It enables analyses with much higher accuracy, without a hot chuck. It also enables evaluating pattern resolutions in the frequency range of nearly diffraction limited cutoff frequency, which could not previously be done by any method. That is surely a breakthrough for application to semiconductor device failure analysis.

The purpose of this paper was to develop optics optimized for the InSb camera to bring out its best performance. We evaluated maximum resolution of the 30×/numerical aperture (NA) 0.71 lens made of silicon and germanium, and achieved the cutoff frequency of around 300 line pairs/mm, which is almost a diffraction-limited performance. The key elements for achieving it were lens design technology enabling both high NA and long working distance (WD) in design (refer to Table 2), and manufacturing technology including polishing and anti-reflection coating.

We also mention here the newly developed thermal microscope THEMOS-1000. Failure locations can be identified rapidly with high precision through the superimposition of a thermal emission image detected by the thermal detector and the pattern image obtained from an IR-confocal laser microscope.

2. Specifications of the Thermal Microscope

The InSb camera with superior sensitivity in the wavelength range of 3.7 to 5.2 μm is provided as the detector. Specifications of the InSb camera are shown in Table 1.

The optical system consists of objective lenses and a relay lens. They are all dioptric systems, designed in the wavelength range of 3.7 to 5.2 μm, the same as the sensitivity of the InSb camera, and use silicon and germanium for lens material which is transparent in the design wavelength.[4] The optical setup is shown in Fig. 1, and the specifications of objective lenses are shown in Table 2. Each objective lens has high-performance in NA and long WD enabling accurate and rapid analysis. The objective lenses are mounted on a turret, and selected by the user for best analysis. Each objective lens has the same parfocal distance of 95 mm, which is the same length as Mitsutoyo products. As shown in Fig. 1, the objective lenses are designed to be finite conjugate, which make images by themselves. (This feature is advantageous to the cost because it does not require a tube lens.) Their aerial images are to be relayed by the relay lens to the InSb detector. The InSb detector is surrounded by cold baffles to reduce thermal radiation noise, so that the relay lens is optimized in design such that its exit pupil is located at a cold aperture to avoid vignetting. The relay lens has a magnification of 0.5× due to mechanical restrictions. Magnification in Table 2 is defined as the combination of the objective lens and the 0.5× relay lens.

3. Manufacturing

Surface reflectance loss of silicon and germanium, which

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Table 1. Specifications of the InSb camera.

Detector	InSb
Spectral sensitivity (μm)	3.7–5.2
Unit cell size (μm^2)	30 × 30
Effective number of pixels	320 × 240
Effective sensor size (mm^2)	9.6 × 7.2
Cooling method	Stirling cycle cooling
Noise equivalent temperature difference at 30 °C (mK)	<25 (typ.)

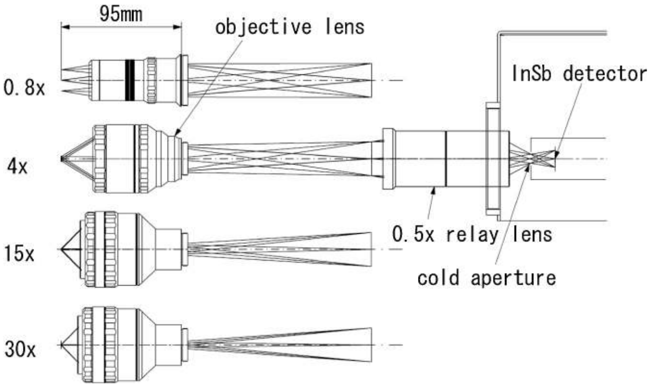

Fig. 1. Optical system for thermal microscopy.

Table 2. Specifications of objective lens.

Magnification (×)	NA	WD (mm)
0.8	0.13	22
4	0.52	25
15	0.71	15
30	0.71	13

is about 30 and 36% per interface, respectively, is dramatically reduced by the anti-reflection coating, achieving less than 1% reflectance per interface in the design wavelength. Both silicon and germanium have much stronger power for refracting rays because of their high refractive indices, so that the tolerance required for polishing these lenses is much more severe than that of a normal glass lens. Especially surface irregularity of those lenses should be controlled to be less than $\lambda/4$ (λ is the wavelength of visible light). Both the 15× and 30× objective lenses are initially aligned to minimize the coma aberration by the structure of the decenter of a lens element, and fixed mechanically after alignment.

4. Experiments

We used a 1951 USAF resolution special target, which conform to MIL-STD-150A, for our analysis. The resolution target format is partially shown in Table 3. Vacuum deposited inconel is used for the pattern material. The pattern is negative type. Sapphire, which is transparent in the design wavelength, is used for the substrate material. The resolution target is illuminated from behind by a full-radiator whose temperature is controllable.

Table 3. 1951 USAF resolution target format.

Group no.	Element no.	Resolution (line paies/mm)
6	1	64.0
	2	71.9
	3	80.7
	4	90.7
	5	102.0
	6	114.0
7	1	128
	2	144
	3	161
	4	181
	5	204
	6	228
8	1	256
	2	288
	3	322
	4	362
	5	406
	6	456

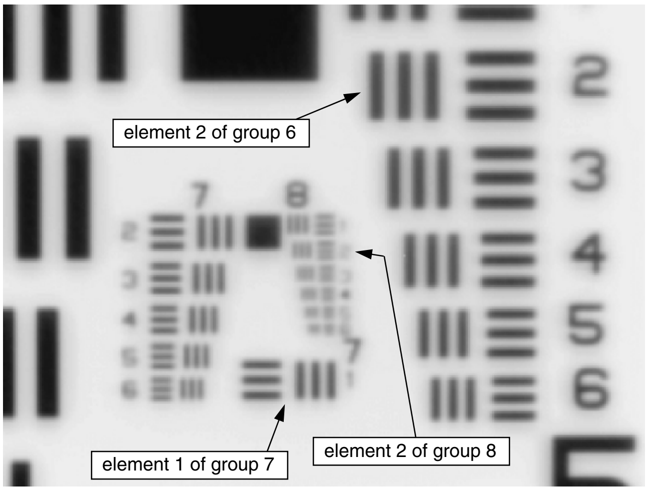

Fig. 2. Pattern image of the 1951 USAF resolution target (refer Table 3) obtained by the developed thermal microscope with 30× objective lens. View area of the image is 320 × 240 μm^2 in object plane.

Actually, we evaluated the performance of the developed thermal microscope using the resolution target. The unit cell size of the InSb camera, which is 30 × 30 μm^2, determined the resolution limit of the 0.8×, 4×, and 15× objective lenses, while the performance of the 30× objective lens determined the system resolution limit because the relative unit cell size of the camera is small enough for its diffraction limit.

The transmission image with the 30× objective lens is shown in Fig. 2. The temperature of the full-radiator was controlled to be 120 °C. The gray scale of the image was adjusted to the pattern of the resolution target. In Fig. 2, we can say that up to element 2 of group 8 was obviously resolved. We evaluated that the MTF at 256, 288 line pairs/mm is 7%, 2% respectively, so we determined that the pattern image achieved the cutoff frequency of around 300 line pairs/mm, which is almost a diffraction limited performance because it is equal to diffraction limited cutoff frequency u_{cutoff} at the design wavelength of $\lambda_1 = 0.0047\,\mathrm{mm}$. That can be calculated by

$$u_{\mathrm{cutoff}} = \frac{2 \cdot \mathrm{NA}_1}{\lambda_1} = \frac{2 \cdot 0.71}{0.0047} \fallingdotseq 300 \text{ line pairs/mm}, \quad (1)$$

where $\mathrm{NA}_1 = 0.71$ is numerical aperture of the 30× objective lens.

5. Applications

The thermal microscope mentioned above is installed on the THEMOS-1000, a product of Hamamatsu Photonics, for thermal emission analysis. 0.8×, 4×, and 15× objective lenses are provided as standard and a 30× objective lens is provided as an option. The optical system of the THEMOS-1000 is shown in Fig. 3(a), and a thermal pattern image of an integrated circuit obtained by the system with a 15× objective lens is shown in Fig. 3(b) as an example. In semiconductor device failure analysis, thermal emission images can be obtained by subtracting the original thermal pattern image.

The THEMOS-1000 system incorporates an IR-confocal microscope, utilizing an infrared laser at a wavelength of 1.3 µm. Failure locations can be identified rapidly with high precision through the superimposition of the thermal emission image detected by the thermal detector and the pattern image obtained from an IR-confocal laser microscope.

Optionally, combining a thermal lock-in unit allows for lock-in analysis. This function suppresses thermal diffusion and eliminates external noise to deliver analysis results with higher sensitivity and resolution.

We anticipate that the THEMOS-1000 will be available for analysis of semiconductor device failure or any other applications to provide rapid feedback with high accuracy.

6. Conclusions

We have developed a thermal microscope which has an InSb detector and optics optimized for the camera. Using this system, we evaluated maximum resolution of the 30×/NA 0.71 lens made of silicon and germanium, and achieved the cutoff frequency of around 300 line pairs/mm, which is almost a diffraction-limited performance. The thermal microscope described in this paper is installed on the THEMOS-1000, a product of Hamamatsu Photonics, for thermal emission analysis.

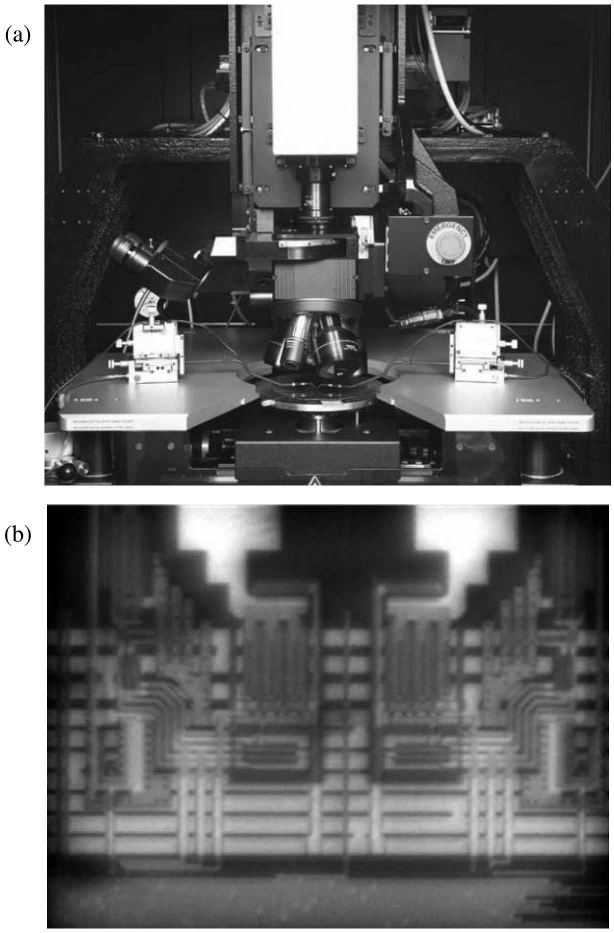

Fig. 3. (Color online) THEMOS-1000 for semiconductor failure analysis. (a) A photograph of the optical system and (b) thermal pattern image of an integrated circuit obtained by the system with 15× objective lens.

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