Invited Paper

Terahertz microscopy and application in semiconductor testing

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Abstract: Terahertz microscopy can be classified into two categories according to resolution, micrometer microscopy and nanometer microscopy. Typical methods for these two kinds of microscopy are analyzed with particular stress on characteristics and potential application value. Some state-of-the-art terahertz microscopy products are introduced, as well as Electro-Optical Terahertz Pulse Reflectometry that utilizes ultrafast terahertz pulses to differentiate and locate faults of integrated circuits in semiconductor failure analysis laboratories. A brief discussion on the potential applications in semiconductor industry compared with other techniques is given in the final part to help those engaged in related research and development activities.

Key words: Terahertz microscopy, Semiconductor Industry, Non-destructive testing.

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1. Introduction

Terahertz microscopy has great potential applications in semiconductor industry and biomedical detection. With the rapidly increasing national investment in semiconductor area and recent ZTE and Huawei events, terahertz non-destructive testing in semiconductor industry has been given high expectation.

However, the wide spread application of terahertz non-destructive testing in semiconductor industry is still yet to come. In this article, the technical roadmap of terahertz microscopy is elaborated along with some typical products, in expectation of helping those engaged in related research and development activities.

Terahertz microscopy can be classified into two categories according to resolution, micrometer microscopy and nanometer microscopy. We firstly review different approaches to these two kinds of terahertz microscopy with emphasis on specific technical characteristics and potential application value. Then some typical products related to terahertz microscopy are introduced, along with Electro-Optical Terahertz Pulse Reflectometry (EOTPR) that uses ultrafast terahertz pulses to differentiate and locate faults for IC. Compared with other techniques, terahertz technique has some superior advantages. But it is still immature in some aspects, like expensive hardware cost and lack of standards in semiconductor industry.

2. Terahertz micrometer microscopy

There are many different ways for terahertz micrometer microscopy. They can be mainly classified into three categories: imaging with locally constrained beam, imaging based on electro-optic conversion, and single detector-compressed sensing method. Some other methods like structured illumination [1] and supper-focusing through meta-material also exist in terahertz band, but these are not the mainstream, and lack practical feasibility. The three mainstream methods are elaborated respectively as follows.

2.1 Localized imaging beam

2.1.1 Imaging beam constrained by sub-wavelength aperture

This kind of terahertz microscopy is accomplished by focusing the imaging sampling light (780 *nm* for GaAs substrate, 1550 *nm* for InGaAs substrate) to micrometer scale through convex lens or pinhole.

As shown in Fig 1(a), the sampling light beam is focused through a convex lens. The terahertz waves illuminate the imaging area. We get the terahertz micrometer microscopy of the sample by raster scanning the imaging area [2].

As shown in Fig 1(b), the sampling light beam is focused through a pinhole. The sample is placed on the GaAs wafer. By raster scanning the terahertz wave illuminated area, the micrometer microscopy of the sample is accomplished [3]. If the pinhole or some sub-wavelength aperture is used to focus the sampling light beam, the high frequency cutoff phenomenon must be taken into account to ensure sufficient signal noise ratio [4].

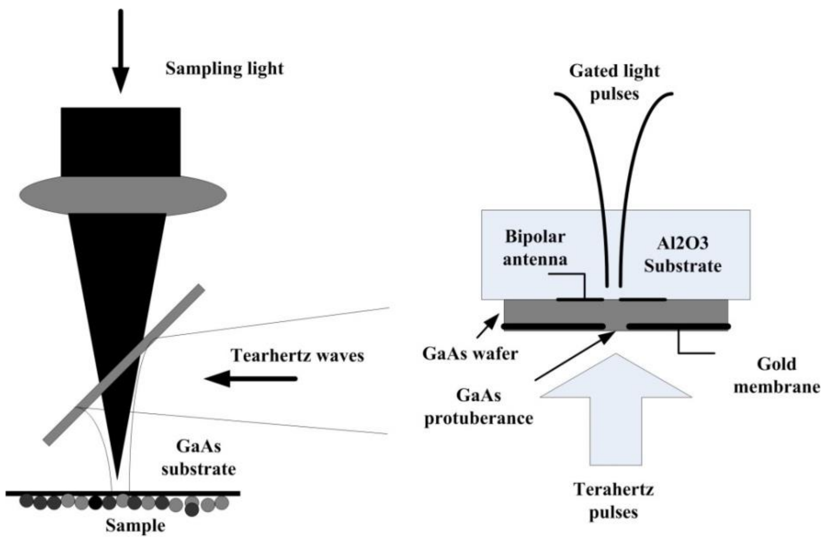


Fig. 1 Terahertz microscopy through localized imaging beam, (a) Optic dynamic aperture; (b) Sub-wavelength pinhole

2.1.2 Imaging beam constrained by microprobe

Terahertz microscopy based on scanning microprobe can be classified as transmission type and reflection type, as shown in Fig 2. This kind of microscopy is different from the imaging system which uses vibrating AFM probe to guide the imaging signals. The emitting terahertz waves, focused by the silicon lens, illuminate the imaging area. The ultrafast probe beam impinges the sample on the other side. The imaging microprobe, connected to lock-in amplifier, detects the near-field interaction information between terahertz waves and the sample. The resolution is determined by the aperture of microprobe which is used as near-field detector, and usually is limited to micrometer scale. The raster-scanning manner means that, it takes a few minutes to tens of minutes to get a typical image. The distance between the microprobe and imaging sample is difficult to control, which makes it unsuitable for coarse sample surface. The microprobe is usually too bristle and should be renewed every time it is break.

This kind of terahertz microscopy has already been developed into commercial product, like Teraspike series from Protemics. It has potential applications in areas like semiconducting thin film inspection, 3D system in package (SIP) fault analysis, and fiber-enhanced composite material inspection.

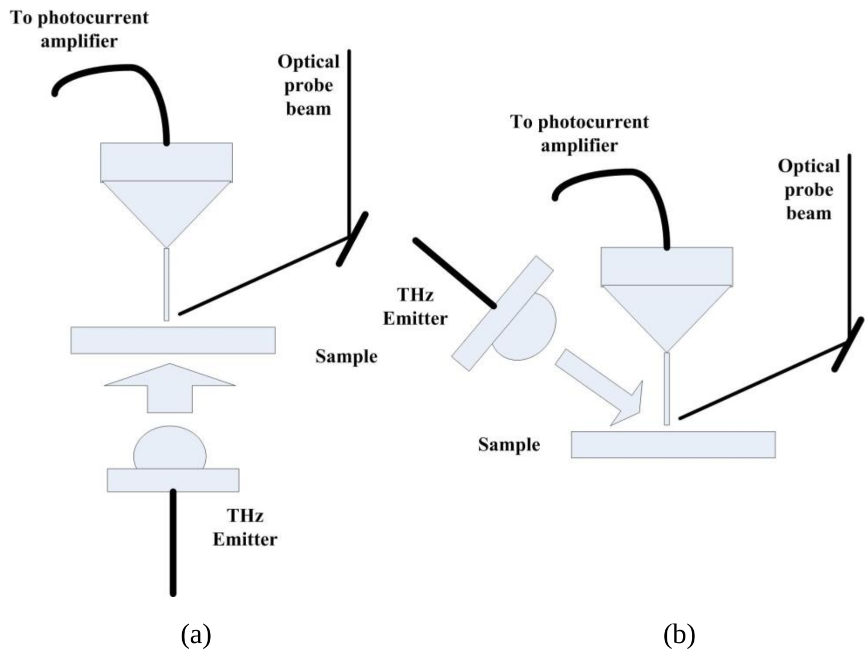


Fig. 2 Terahertz near-field microscopy through raster-scanning microprobe, (a) transmission; (b) reflection

2.2 Imaging based on electro-optic (EO) conversion

Various ways to transfer terahertz imaging information to other bands are investigated to avoid the immature and costly high resolution imaging arrays of terahertz band. Once the terahertz imaging information is transferred to the other band, more mature device of this band can be used, and the imaging resolution and speed can be enhanced a lot. The most common way is electro-optic (EO) conversion.

Generally, there are two ways, as shown in Fig 3. One method is by focusing the ultrafast laser pulses through a microscope objective and raster scanning the imaging sample [5]. The sample is placed upon the surface of the EO wafer (ZnTe, $LiNO_3$, etc). The imaging speed is slow due to the scanning manner. The other method is illustrated as Fig 3(b). The interaction information between terahertz waves and sample is transferred to the detection beam. The image is magnified by convex lens and recorded by CCD camera. As the terahertz microscope images can be recorded frame by frame, the speed is only limited by the CCD camera and EO effect response time. This can be utilized to implement ultrafast real-time microscope imaging as shown in Fig 4. The resolution can be 10 *um* or even higher, and the response time can be a few picoseconds, which is fast enough to record ultrafast phenomenon of semiconductor wafer [6].

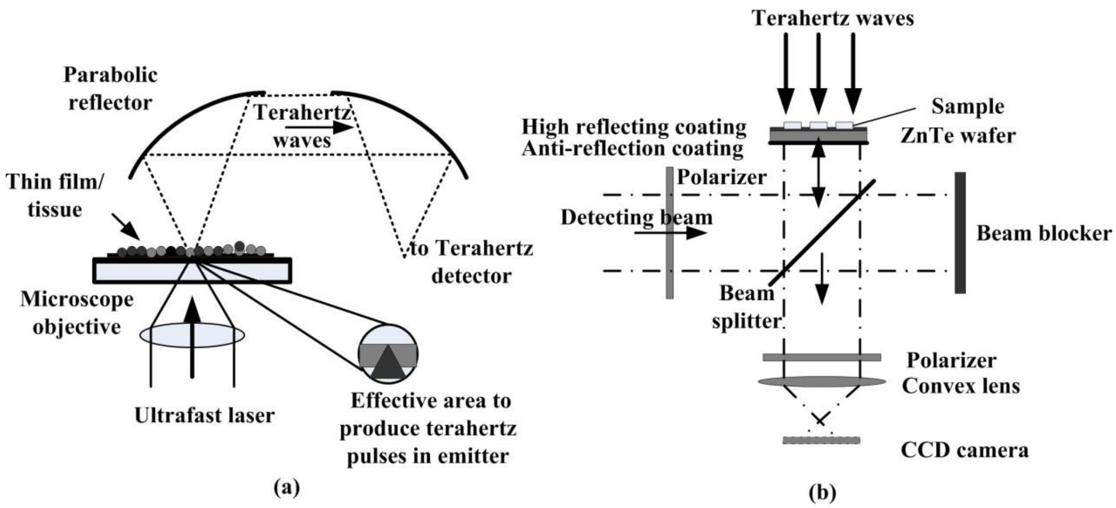


Fig. 3 Terahertz near-field microscopy based on electro-optic conversion (a) Ultrafast laser focused by microscope objective, (b) terahertz imaging information converted to detecting beam, magnified by convex lens, and captured by CCD camera.

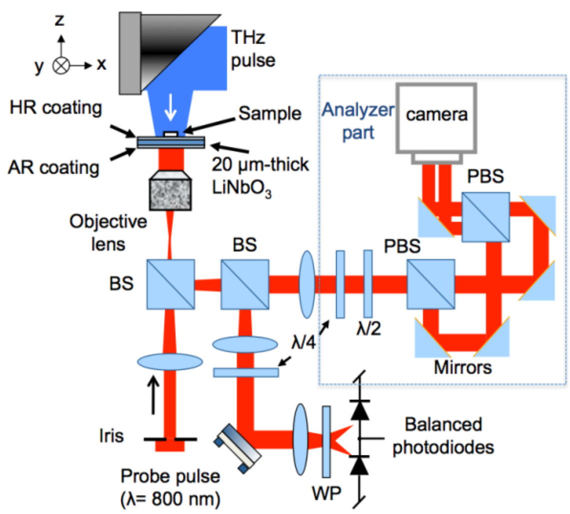


Fig. 4 Terahertz real-time near-field microscopy system based on EO conversion

2.3 Single detector-compressed sensing

One research group from University of Glasgow invented the so called single detector-compressed sensing system to implement terahertz microscopy [7, 8]. The schematic imaging system is shown as Fig 5. The pump pulse impinges the digital mirror device (DMD), which encodes the pulse pattern and transmits to a silicon wafer. The encoded pattern interacts with the silicon wafer to control the on and offs for each pixel locally. This method utilizes the DMD in the pump light band and the EO effect between the terahertz waves and silicon wafer to accomplish the digital modulation of spatial mask. The imaging object attached to the thin silicon wafer is illuminated with the modulated spatial pattern, which is then collected by a single-element detector. By changing the DMD pattern, a series of modulated spatial patterns can be obtained. The high resolution terahertz microscopy can be reconstructed via compressed sensing algorithm. According to the literature, the resolution can be as high as 10 *um*.

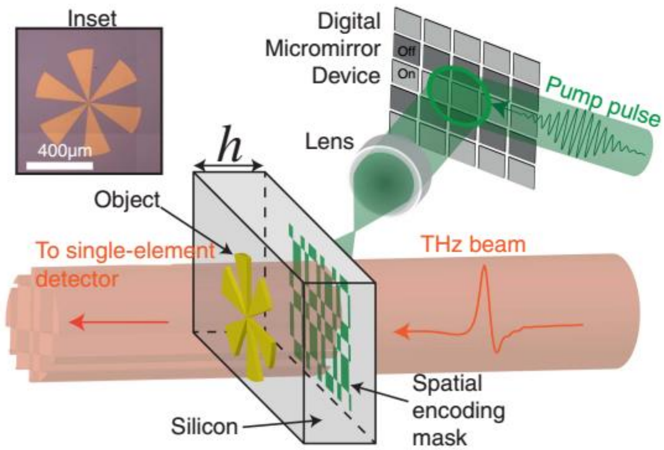


Fig. 5 Terahertz single detector-compressed sensing microscopy

3. Terahertz nanometer microscopy

The application of terahertz nanometer microscopy has mainly been confined in scientific research area, like none-evasive inspection for quantum dot and quantum line, semiconductor fault analysis in nanometer scale. There are generally two types of systems, scattering-type scanning near-field optical microscopy (s-SNOM), and terahertz scanning tunneling microscopy (THz-STM). Both types require the scanning step to acquire a full frame image, which slows down the imaging time to a few minutes. The imaging principles are elaborated schematically as follows.

3.1 THz s-SNOM

THz s-SNOM system generally uses the AMF tapping tip to guide the imaging signals locally, and the locking-in amplifier to detect the weak scattering signals, as shown in Fig 6. The metal tip vibrates with a baseband frequency, and the lock-in amplifier detects the weak scattering signals by locking at a certain times of baseband frequency to get rid of background radiation.

The effective signal the tip interacts with the sample is illustrated as equation (1)

$$E_s \propto \alpha_{eff-tip}(1+\gamma)^2 E_i = \sum_{n=0}^{\infty} \sigma |F_n| E_i \exp(jn\Omega t + j\varphi_n) \tag{1}$$

$$\alpha_{eff-tip} = F_0 + F_1 \exp(j\Omega t) + F_2 \exp(j2\Omega t) + \ldots = \sum_{n=-\infty}^{\infty} F_n \exp(jn\Omega t) \tag{2}$$

E_s is related to the sample's conductivity ε_s which can be viewed as the fingerprints of the sample. The common detection schemes in s-SNOM include self-homodyne detection, homodyne detection, heterodyne detection, pseudo-heterodyne detection and synthetic optical holography [9]. According to public report, there exist two kinds of THz s-SNOM system, all electronic type and ultrafast type.

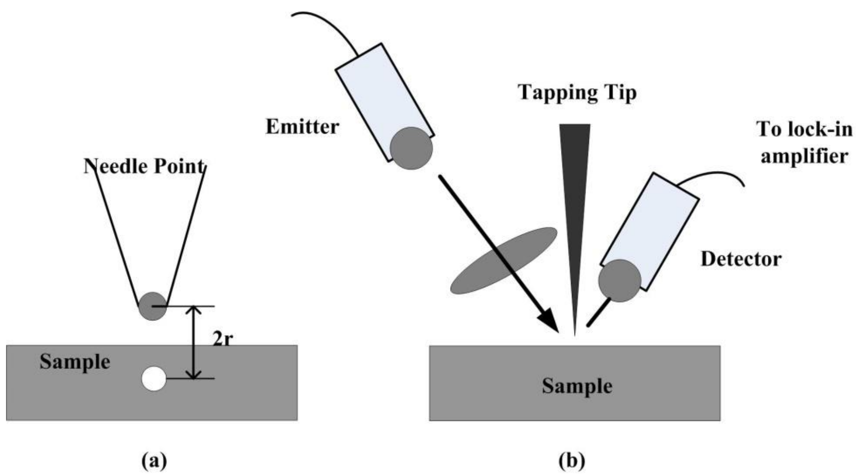


Fig. 6 Tapping tip guided SNOM system

A. All-electronic type

The all-electronic type means that the source and detector of the imaging system are made of solid-state electronics, as shown in Fig 7. The terahertz microscopy system, based on all-electronic transceiver with the multiplication chain custom-built by Virginia Diodes Inc, is compact and can be integrated into one box [10]. It attracts much attention because the system can be used to quantify conductivity of lowly doped semiconductors on the 50 *nm* scale, and identify the carrier type and density in a few minutes acquisition time.

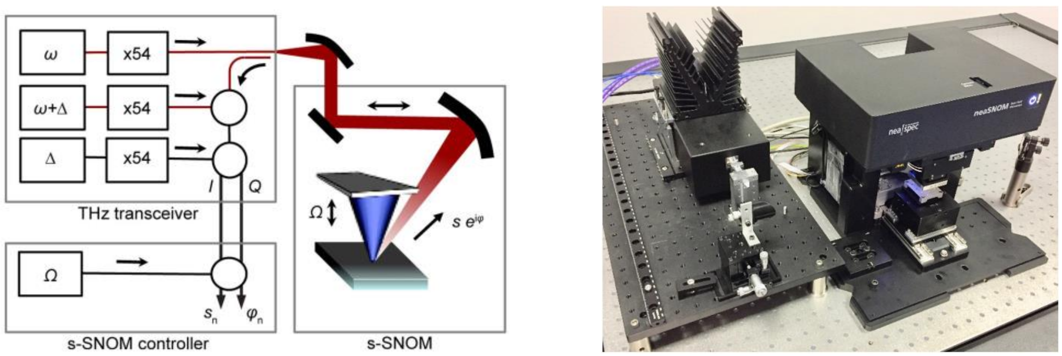


Fig. 7 All-electronic terahertz SNOM, (a) the schematic system construction, (b) integrated product, neaSNOM

B. Ultrafast type

The ultrafast type means that the s-SNOM system is integrated with optical pump-terahertz probe system, as shown in Fig 8. It can be used to imaging the semiconductor nano-line in nanometer scale with 10 *nm* spatial resolution and picoseconds of time resolution [11]. If we use the difference frequency method to generate terahertz pulse, the tuning range can be much wider, about 20-50 *THz*. This type of terahertz s-SNOM system can be used to investigate the ultrafast phenomena of semiconductor in nanometer scale. Up until now, there is no commercial compact product based on this scheme.

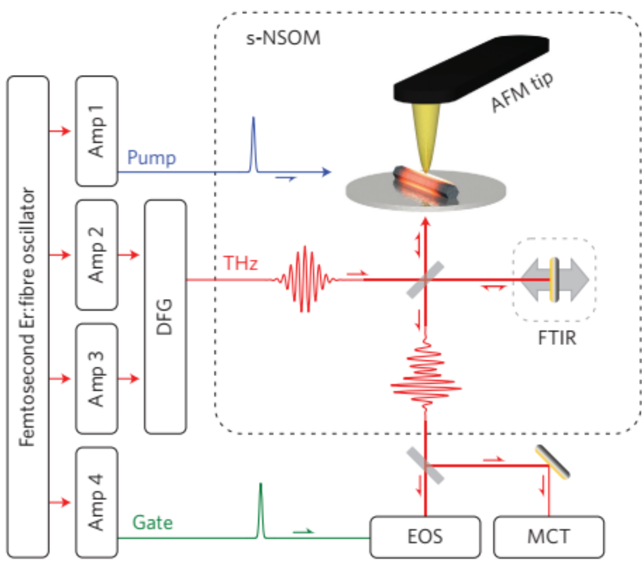


Fig. 8 THz s-SNOM integrated with ultrafast pump-probe system

3.2 THz-STM

Scanning tunneling microscopy (STM) can be used in surface characterization of semiconductor in atomic scale. Integrate the STM system into the optical pump-terahertz probe system, terahertz microscopy with nanometer resolution and picosecond time resolution can be acquired, as shown in Fig 9. It utilizes the nonlinear current-voltage (I-V) relation of a tip-sample tunnel junction to produce a modulated tunneling current burst in a process associated with junction-mixing STM [12]. The result published in Nature Photonics evoked efforts to build THz-STM system as a scientific instrument.

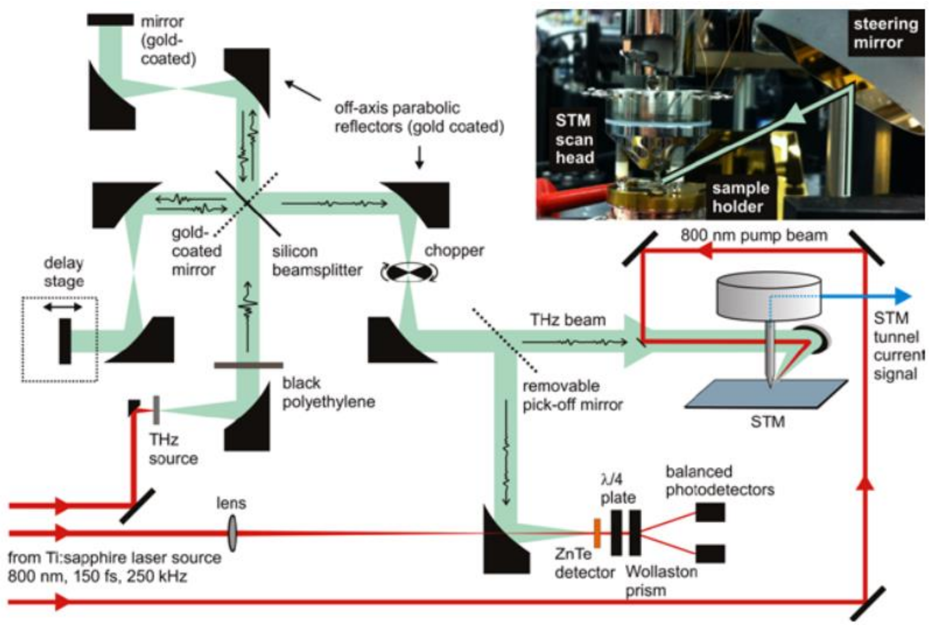


Fig. 9 Terahertz scanning tunneling microscopy

4. Typical products of terahertz microscopy

There are several national institutions investigating terahertz microscopy and related applications in semiconductor inspection and biomedical imaging, including Shanghai University of Technology, Tianjin University, Chinese Academy of Sciences, and Chinese Academy of Engineering Physics. But compact commercial terahertz microscopy products in China is still lacking. Typical products worldwide include Teraspike series of Protemics and NeaSNOM system of Neaspec. Both are German companies and take institutions as their potential customers.

The compact terahertz microscopy system of Protemics, as shown in Fig 10, can achieve about

10 *um* resolution. There are a series of microprobes developed for transmission and reflection imaging. And a special kind of microprobe, TeraSpike XR-option, is suitable for coarse surface characterization. The compact system can also be used as TDR to detect the open end reflection on transmission lines.

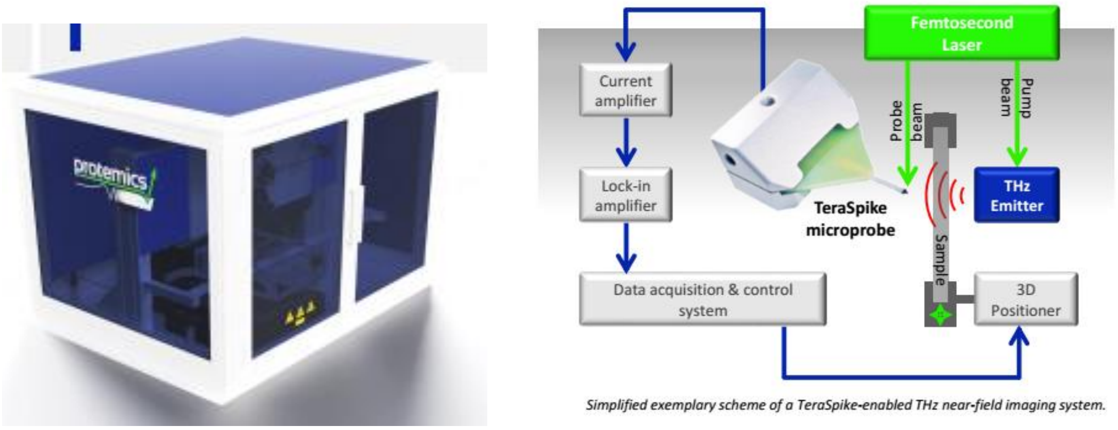


Fig. 10 Compact terahertz microscopy system of Protemics

The Neaspec company focuses on high resolution spectroscopy and nanometer imaging ranging from visible light, near infrared, mid-infrared, far-infrared, to terahertz waves, and also takes the institutions as customers. It provides advanced investigating tools that are effective in nano-photonics research, and remains the only company in the world that can accomplish nanometer scale imaging in such wide bands from visible light to terahertz waves.

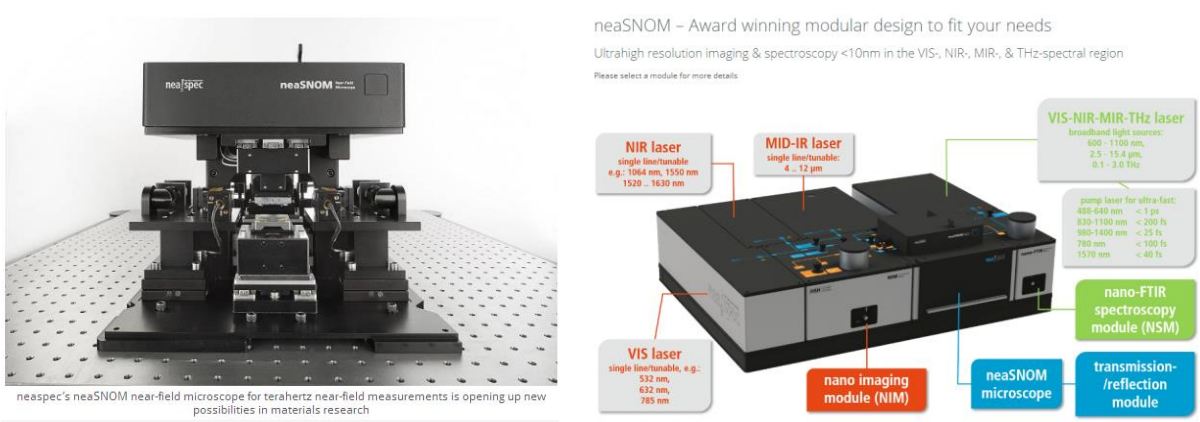


Fig. 11 neaSNOM system from Neaspec. (a) Terahertz neaSNOM, (b) Integrated ultrahigh resolution spectroscopy and imaging system

5. EOTPR/TDR for IC fault analysis

Terahertz pulses in the time domain can be used as quality analysis tool to locate and clarify the fault of 3D system-in-package (SIP) in semiconductor industry. Though this tool cannot be classified as terahertz microscopy system, it sets a successful example for terahertz microscopy to follow.

Electro-Optical Terahertz Pulse Reflectometry (EOTPR) as shown in Fig 12, consisting of three basic parts, terahertz wave generation and detection part based on ultrafast laser and photoconductive antenna (PCA), probe station and DUT part, read out circuit and analysis part. The system utilizes the microprobe guided terahertz pulses, not the microscopy images to analyze the IC faults.

The performance comparison between EOTPR and traditional TDR system is given in Table 1. The EOTPR has higher range resolution and SNR, which is suitable for 3D package failure analysis that traditional TDR is incapable of [13, 14]. The EOTPR 2000 and EOTPR 5000 system have already been used in semiconductor failure analysis laboratories in AMD, IBM, Intel and TSMC. One example that illustrates how EOTPR can be used to locate fault in IC is shown as Fig 13.

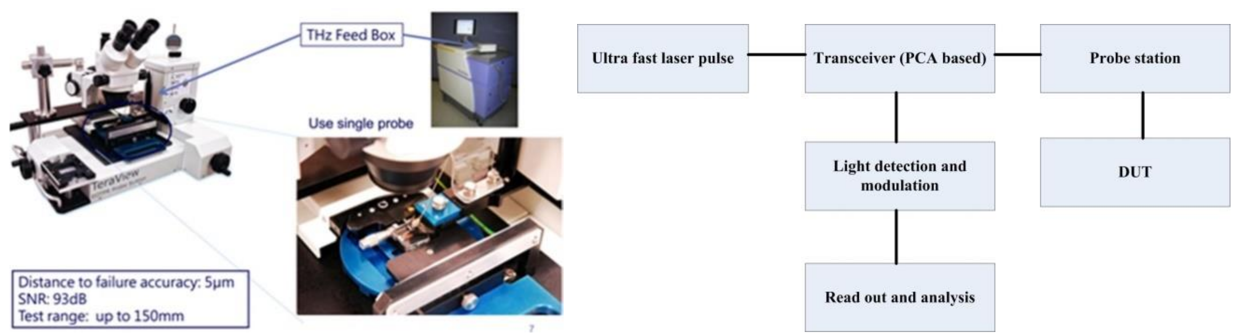


Fig. 12 Electro-Optical Terahertz Pulse Reflectometry (EOTPR) system from TevaView. (a) the outlook of system, (b) the schematic construction

Tab. 1 Performance comparison between EOTPR and traditional TDR

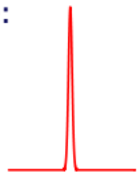
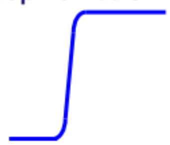
Property	EOTPR	TDR	Remarks
Incident Signal	Pulse: 	Step function: 	
Frequency range	110 GHz	20 GHz	Higher bandwidth
Rise time	<6 ps	>17.5 ps	Faster rise time produces better resolution
Time base jitter	<30 femtoseconds	>500 femtoseconds	Low jitter with high time base stability
Signal to noise (max)	93 dB	45 dB	Better SNR increase sensitivity of impedance change

Fig. 13 One example from Intel that uses EOTPR to locate fault in IC

Advantest Company also develops THz-TDR system that uses terahertz pulses to locate the open failure in IC. Fig 14 illustrates how THz-TDR can be used in IC failure analysis.

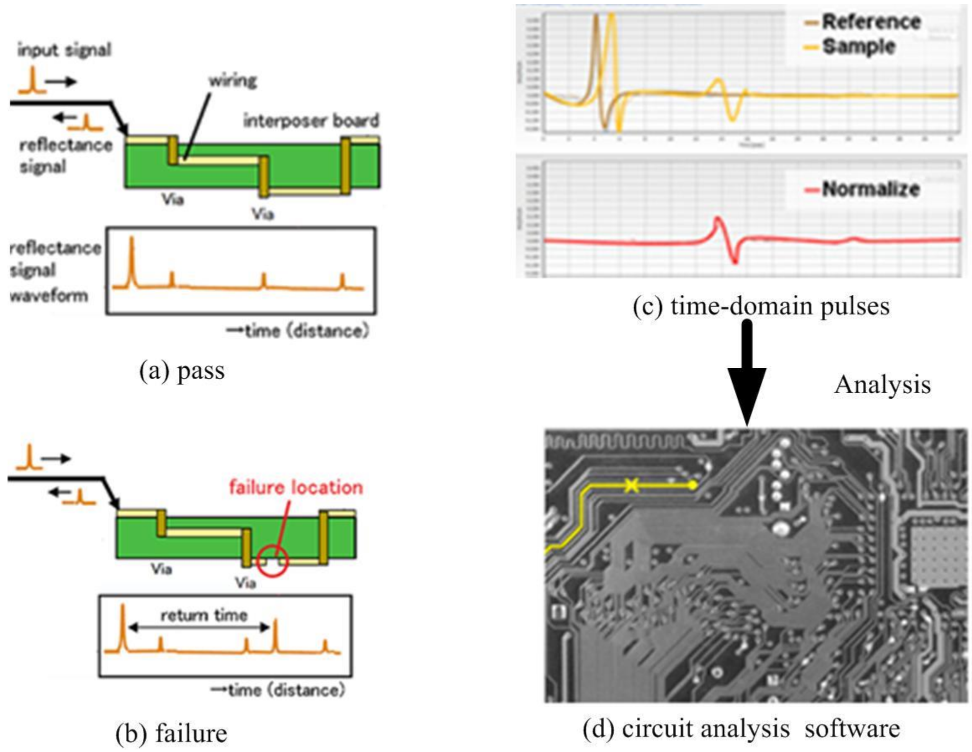


Fig. 14 Example that illustrates how THz-TDR systems work to locate IC failure

6. Technical summary and discussion on semiconductor industrial application

The super-resolution microscopy is a traditional, yet vigorous research topic. It opens the secret door to the micro-world. Terahertz microscopy is characterized by high resolution in both spatial domain (micrometer or nanometer scale) and time domain (a few picoseconds). It has great potential applications in semiconductor inspection for both scientific and industrial purposes.

This article covers the mainstream techniques and imaging system products related to terahertz microscopy. The terahertz super-resolution techniques in micrometer scale are more mature than that of nanometer scale. A few methods that use non-scan manner to acquire terahertz images with high speed can satisfy the industrial need. Those methods are promising for product development of semiconductor industrial inspection.

Currently, terahertz microscopy has witnessed two typical types of products, Teraspike series from Protemics and NeaSNOM from Neaspec. Both of them take research institutions as their main customers.

TeraView Company and Advantest Company are the vanguards to use microprobe guided terahertz pulses in semiconductor failure analysis, because both of them have strong relations in semiconductor industry. Although these products do not use the terahertz microscopy images, EOTPR and THz-TDR can be a model to follow.

However, the wide spread applications in wafer and thin film inspection, and nanometer scale process line are still yet to come. The status of visible light microscopy and X-ray microscopy is still unchallenged in IC and PCB none-destructive testing. The traditional methods can find over 97% conventional faults.

Terahertz microscopy needs to utilize the complementary advantages to get recognized by semiconductor industry. The terahertz microscopy system for semiconductor industrial application should be developed alongside with IC designers and engineers from semiconductor failure analysis laboratories. Only through this way can it be put into practical use.

Acknowledgement

This article provides a brief review of terahertz microscopy and related technology and products that are especially useful in semiconductor NDT. Some figures are adapted directly from the literature without any change. I am also grateful for the helpful discussion on EOTPR with Walter Chen from the ACE solution Company.

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