# Effective testing for wafer reject minimization by terahertz analysis and sub-surface imaging

**Article** · May 2014

DOI: 10.1109/ASMC.2014.6847013



**2 authors:**

Anis Rahman
Applied Research & Photonics
**107** PUBLICATIONS **289** CITATIONS
SEE PROFILE

Aunik K Rahman
**56** PUBLICATIONS **99** CITATIONS
SEE PROFILE

# Effective testing for wafer reject minimization by terahertz analysis and sub-surface imaging

Anis Rahman and Aunik K. Rahman
Applied Research & Photonics
470 Friendship Road, Suite 10
Harrisburg, PA 17111, USA
a.rahman@arphotonics.net

***Abstract*— This paper outlines applications of terahertz spectrometry, terahertz reflectometry and sub-surface imaging for effective characterization of various aspects of semiconductor wafer testing. Exemplary results of scanning a wafer have been analyzed for defect determination. Additionally, terahertz reflectometry for controlling wafer polishing for planarization has been exemplified via high precision thickness monitoring. Application of terahertz spectrometry for identifying self-assembled monolayer (SAM) on a wafer is also outlined with example. The technique may be extended to other substrates transparent to terahertz radiation. Characterizing different SAM coated silicon wafers for identifying two different SAM species has been discussed. The Fourier transform absorbance spectra of both SAM specimens reveals several distinguishable absorbance peaks that may be used as signatures of the respective SAMs. The SAM having 18 carbon chain exhibits higher absorbance than that of the SAM comprised of 8 carbon chain. This is consistent with the higher molecular weight of the former.**

***Keywords—Terahertz spectrometry; Terahertz reflectometry; Terahertz scanner; sub-surface imaging; wafer defect analysis; Wafer thickness monitoring; Self-assembled monolayer on wafer***

## I. INTRODUCTION

Terahertz spectrometry [1] and reflectometry [2] offers an effective solution for wafer reject minimization by means of sub-surface, nano scale, 3D imaging, via a non-destructive and non-contact route. A terahertz sub-surface 3D imager (Applied Research & Photonics) has been used for the current investigations. Simultaneous reflection and transmission measurements allow inspection of semiconductor wafers during fab processes (in-situ) as well as for post-fab characterizations (ex-situ). The intensity of the reflected terahertz beam is proportional to the specific features (layers) of the specimen under test. Therefore, measured intensity may be modeled in terms of suitable physical parameters such as refractive index, density, dielectric constant, etc., via a modified Beer-Lambert's law. For a given wafer, all material parameters remain unchanged during measurements, because, terahertz radiation is non-ionizing and does not perturb the intrinsic properties. Thus, the reflectance, $R$, is proportional to the variations in materials at the point where the beam is incident. As such, the reflectance is dependent on the spatial and angular coordinates: $R(x, y, z, \theta)$. A 3D reconstructed image generated from reflectance, therefore, will yield the characteristic features (patterns) on the substrate. Another advantage of the terahertz scanner is that silicon and other semiconductor wafers are transparent at these wavelengths. Therefore, scanning may be done across the thickness of a wafer for inspecting internal layers. So, if there is a hole or void on the substrate or in any of the sub-surface layers, that will be identifiable from both reflected and transmitted intensities. Based on the above principle, a signature of a given defect may be established. Any defect such as, inclusions, cracks, non-uniformity, or particulate foreign material can be detected and identified by this technique. Moreover, defect size may be estimated from either a 2-D scan, or 3-D scanned reconstructed imaging. The terahertz nano-scanner deploys a non-contact measurement system with an adjustable stand-off distance. The sample space is adjustable to accommodate required sample size. A rotary axis enables examination of a wafer (or other sample) from different viewing angles. This is important because cracks or other non-uniformities might not be along a straight line-of-sight. Thus an angular scan enables viewing hidden features. In addition, with the advent of the angular axis, one can scan cylindrical objects in a conformal fashion.

Another important issue for the semiconductor wafers is the requirement of planarization as the fabrication process progresses with layer by layer deposition and patterning. Chemical and mechanical polishing (CMP) used for wafer planarization requires just sufficient material to be removed, but too much removal can result in failure/rejection of the wafer. As such precise thickness control, on the order of nanometers, is required for lowering the reject rate. Terahertz transmission and/or reflection measurements can be used for monitoring the CMP process. Here, we report a technique for controlling the polishing process based on given thickness criterion. The removal of material from the wafer surface is a complex function of the polishing slurry, spin speed and duration, among other factors. However, a straightforward

method that minimizes monitoring of individual variables is the direct measurement of the thickness of the wafer, from which the mass of the removed material may also be calculated. In this technique a terahertz beam is reflected off of the polishing surface while a transmission measurement may also be carried out simultaneously. A requirement of this technique is a rigorous calibration of the material removal as a function of polishing conditions while all physical parameters essentially remain fixed. This process reduces the number of control variables to a single parameter, i.e., reflected (and/or transmitted) power vs. thickness removed.

Additionally, semiconductor wafers' surface needs to be modified for different chemistry in preparation of processes such as patterning of waveguides or CMOS process with different functionalities. Common surface modification involves making a wafer hydrophilic or if it is already hydrophilic then converting it to hydrophobic. This is uniquely done by various self-assembled monolayers (SAMs). However, it is difficult to characterize the SAMs with common laboratory instruments (e.g., UV/Vis, Raman or FTIR), because, SAMs being only one molecule thick layer, physical characterization between different SAMs applied on wafer surfaces is challenging. Terahertz spectroscopy offers an advent of characterizing the molecular systems – even with minimal structural and mass differences – owing to its ultra-high sensitivity stemmed from the fact that terahertz photons interact with the entire molecule as opposed to a bond or a charge states as used by its predecessors.

In the followings, exemplary results of wafer scans have been analyzed for defect determination. Additionally, terahertz reflectometry for wafer polishing has been exemplified with data. Finally, application of terahertz spectrometry for identifying self-assembled monolayer (SAM) on a wafer is also outlined with example.

## II. Experimental

Fig. 1 displays a schematic diagram of the terahertz nano-scanner. Here the wafer is mounted on a rotary stage which is mounted on a XYZ stage. The measurement system comprises of an electro-optic dendrimer based continuous wave (CW) terahertz source and a matching detection system that was described elsewhere [3]. All positioning stages are automated; the linear stages have a resolution of ~25 nm. As shown in Fig. 1, this design is based on normal incidence of the terahertz beam to the target. In case of normal incidence, the incident beam is the sum of the reflected, transmitted, absorbed and scattered intensities. Assuming the material properties remain unchanged during measurement, the reflectance will be proportional to the material characteristics. Ordinarily, the Beer-Lambert's law is used to determine the concentration, $C$, of a solute in a solvent from absorbance data: $A = \varepsilon l C$, where $l$ is the path length and $\varepsilon$ is the extinction coefficient (or molar absorptivity). Since the reflectance, $R$, is material dependent, a modified Beer-Lambert's law may be stated as,

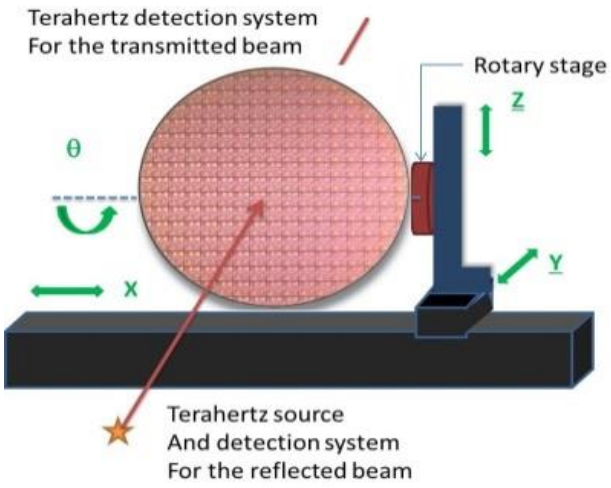


Figure 1. Schematic representation of the nano-scanner.

$$R(r) = \varepsilon(r).l(r).\rho(r), \qquad (1)$$

where, the reflectance is coordinate dependent because the materials on a wafer is position dependent, which in turn causes variation in the path length, $l(r)$, and consequently variation in the coefficient $\rho(r)$. It is notable that, the coefficient $\rho(r)$ may be used for modeling desired material parameters such as density, dielectric constant, refractive index, etc. Obviously, this modeling gives the effective value of the chosen parameter as opposed to the complex quantity. Mapping of $R(r)$ yields a 3D visualization of the specimen. Fig. 2 shows a 3D surface plot of a wafer where different features are depicted by different colors and their sizes are as indicated by the coordinates of the axes.

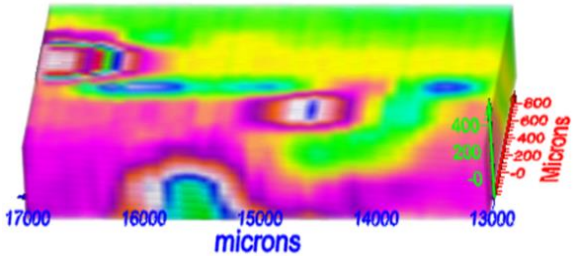


Fig. 2. A 3D image of a wafer area.

## III. Results and Discussion

### A. Wafer inspection

Fig. 3 shows a pattern of adjacent dies on a wafer revealed by a 1D scan. Fig. 3 also shows that adjacent layers are detectable by their unique reflected intensity. A high resolution scan thus clearly shows the start, the end, and intricate pattern for each die on a wafer (Fig. 3 lower plot). The repetitive pattern from high resolution scan serves as a distinguishing

metric for good dies from the bad ones. Since the scans are in exact coordinates, one can inspect the patterns closely for their irregularity and/or defect conditions. Once a defect position is identified, insight from process parameters may be used to

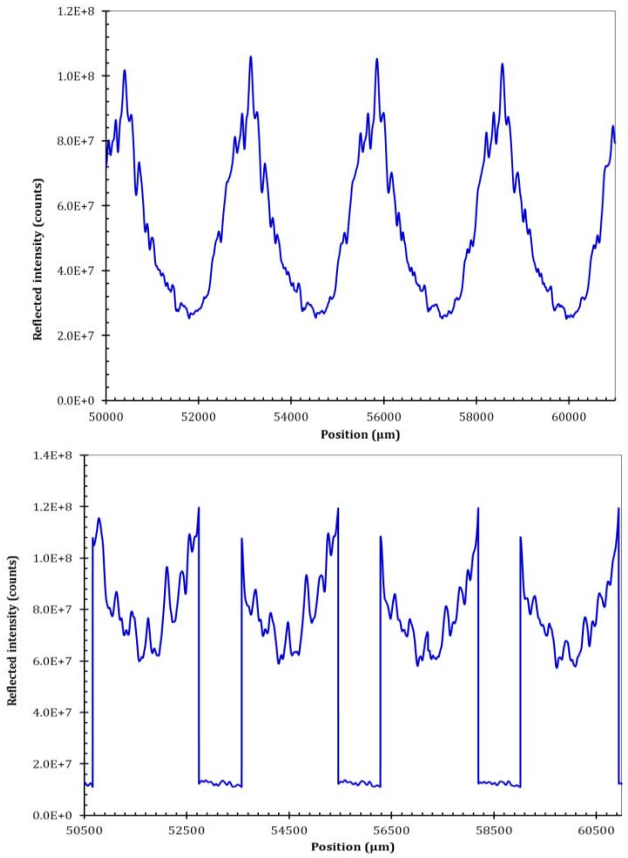


Fig. 3. High resolution scan pattern from two different segments of a wafer. Both top and bottom segment clearly show the start, end, and intricate pattern for each die.

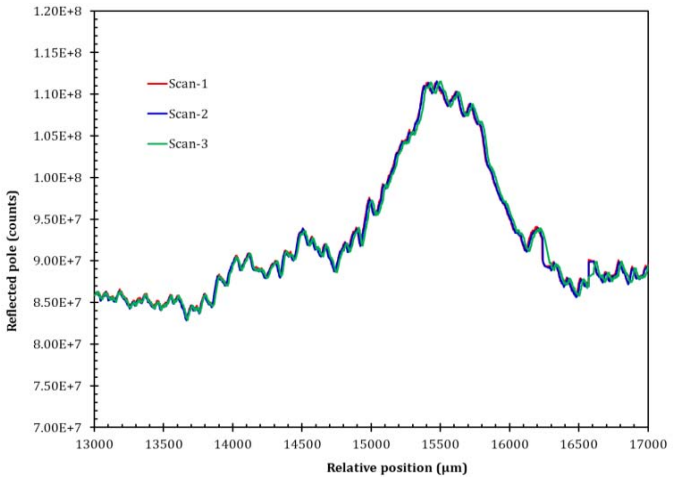


Fig. 4. Reproducibility of the traces. Slight mismatch is due to the course resolution of the stage.

deduce the actual nature of the defect. Fig. 4 shows the reproducibility of the measurements. Fig. 5 shows a reconstructed sub-surface image of an area; a comparison of such images between a good and a bad area will reveal the exact position and layer of the defect.

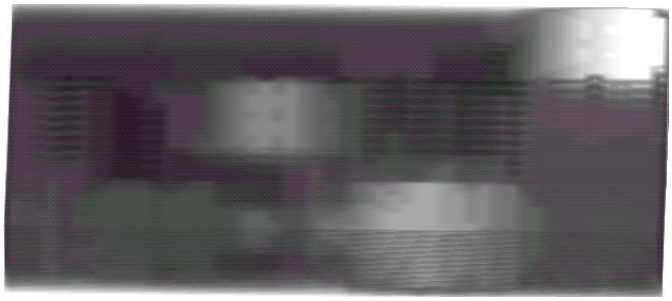

Fig. 5. Reconstructed 3D representation of problem area. A series of 1-D scan in the X-direction was made at different heights to reconstruct the 3-D profile. Some small features are visible.

### *B. Wafer polishing*

In order to demonstrate the resolution of mass removal of a silicon wafer by polishing, a piece of Si-wafer was gradually polished by hand on an 800-grit sand paper. The wafer was weighed after each polish by a lab microbalance, mounted on the THz spectrometer (Fig. 6) and transmitted power (in counts) vs. the removed mass was recorded. Fig. 7 shows that as the mass is removed by polishing, the transmitted power increases successively for each polish, indicating that transmitted power is an inverse function of removed mass. The results were used for computing the corresponding thickness from known area and density of the wafer. Fig. 8 shows the computed thickness vs. the change in measured power. The slope of Fig. 8 indicates that for each nanometer thickness removed, the counts difference is 8.15 million. The noise floor of the detection system is $\sim \pm 5\times10^3$ counts. Thus, the uncertainly in the thickness data of Fig. 8 is $< \pm 10$ *pm*. Therefore, it is demonstrated that THz transmission measurement can be used for high precision thickness monitoring of wafer's planarization process. Thus, a control system operated by this monitoring system is expected to maintain high level of uniformity of the CMP process. However, the actual CMP process involves use of polishing slurry and other chemicals. Therefore, the performance of this system must be determined via calibration for an actual CMP system. In addition, different calibration will be necessary for different slurry and polishing protocol combinations.

### *C. Self-assembled monolayers on wafer*

Self-assembled monolayers (SAMs) were fabricated on double side polished silicon wafers [4]. Two different SAMs have been used. (1): n-Octadecyltrichlorosilane (abbreviated as C-18), Mw = 387.93 g/mol; and (2): 7-OCT-1-Enyltrichlorosilane (abbreviated as C-8); Mw = 245.65 g/mol. The experimental setup was described elsewhere [1]. As received SAM coated wafers were mounted on the spectrometer with similar arrangement as shown in Fig. 6. Terahertz time-domain spectra were acquired with the TeraSpectra front end [5]. Fig. 9 shows the comparison of time-domain signals of the two samples. The SAM C-8, having lower number of carbons, exhibit higher transmission

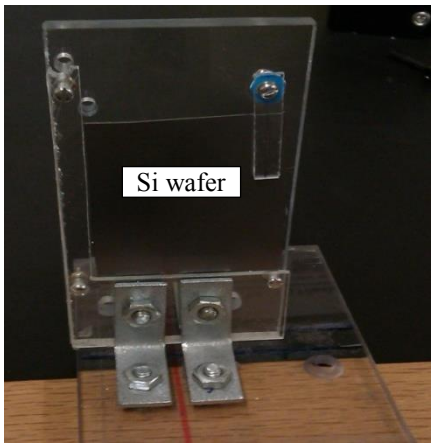


Fig. 6. A piece of Si-wafer mounted on a fixture for polishing experiment and analysis by THz spectrometry. The mount ensures positioning of the wafer at the same place after every polish.

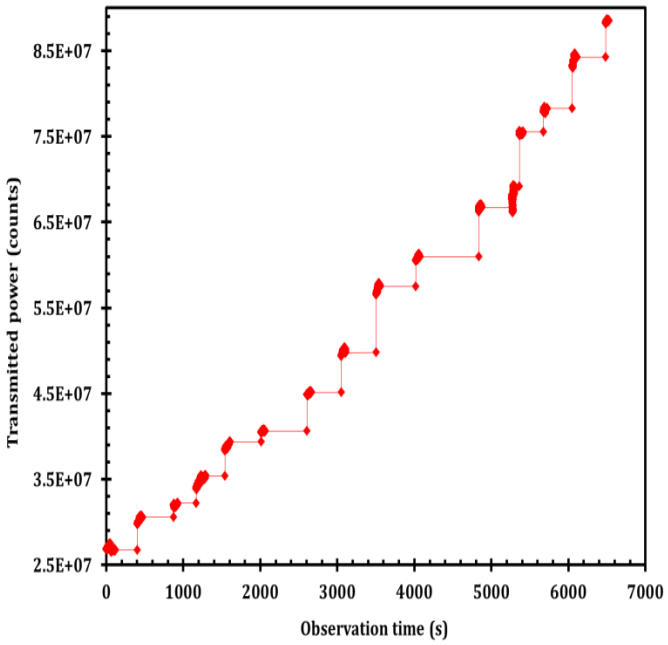


Fig. 7. Transmitted power (counts) increases as a function of removed mass of wafer by polishing.

compared to the SAM C-18. The Fourier transform absorbance spectra of both specimens are shown in Fig. 10. Here also the C-18 SAM-wafer exhibits higher absorbance than that of C-8 SAM-wafer; consistent with the higher Mw of C-18. Fig. 11 shows a close-up of Fig. 10 where several peaks are identified by their frequency that may be used as distinguishing features between the two SAMs. The absorbance of C-18 SAM is always higher than that of C-8 SAM; this observation is consistent with C-18's higher Mw. The spectra shows clear identifying characteristics between the two SAM species (see Fig. 11).

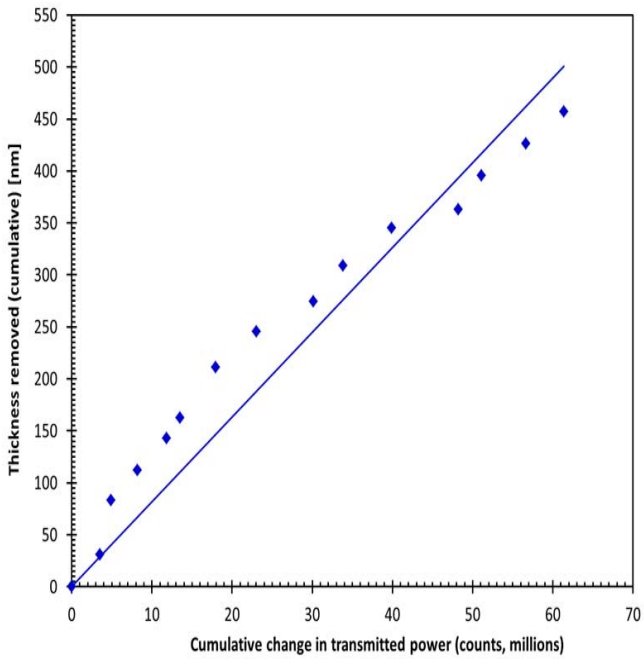


Fig. 8. Computed cumulative layer thickness removed vs THz transmitted power (counts). The data is fitted by y = 8.15x, where x is in millions.

## IV. Summary and Conclusions

In summary, a terahertz scanner has been used to detect defects in a semiconductor wafer. A high resolution scan clearly shows the start, the end, and intricate patterns for each die on a wafer. Since the scan is in scale in all three dimensions, the defect position may be pin pointed. Terahertz reconstructed imaging allows visual inspection of wafers both on the surface and also the layers under the surface in a non-destructive fashion. All measurements are done by non-contact means. It is also demonstrated that terahertz transmission measurements may be used with high precision for monitoring and controlling wafer CMP process. The technique may be extended to other substrates transparent to terahertz radiation. We also demonstrate that terahertz spectroscopy can be effectively used to identify different SAM coated silicon wafers for the SAM species. Two SAMs used here are 8 and 18 carbons long, respectively. The C-18 SAM-wafer exhibits higher absorbance than C-8. This is assigned to the higher molecular weight of C-18. The Fourier transform absorbance spectra of both specimens also exhibits higher absorbance for C-18 than that of C-8 SAM-wafer. This is also consistent with the higher Mw of C-18. Thus the terahertz system of the present study offers a reasonable and accurate solution for different aspects of wafer inspection, thereby aiding to reduce the wafer rejects during fabrication.

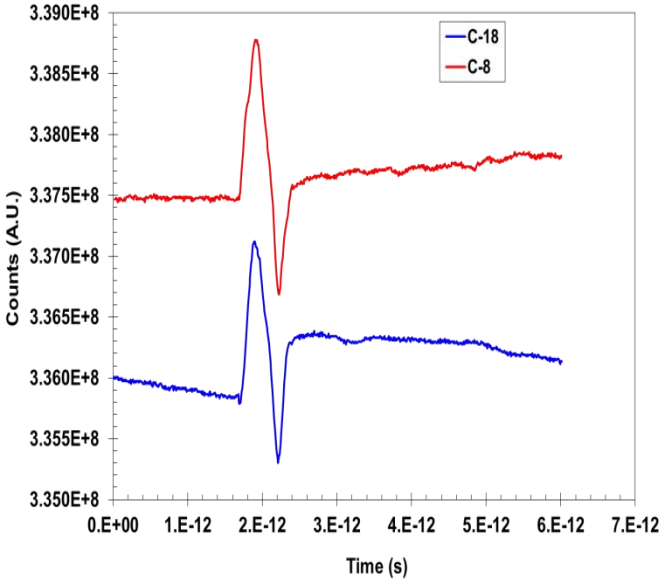


Fig. 9. Temporal signal of silicon wafer coated with two different SAM. C8 having 8 carbon chain has a higher transmission compared to C18, an 18 carbon chain molecule.

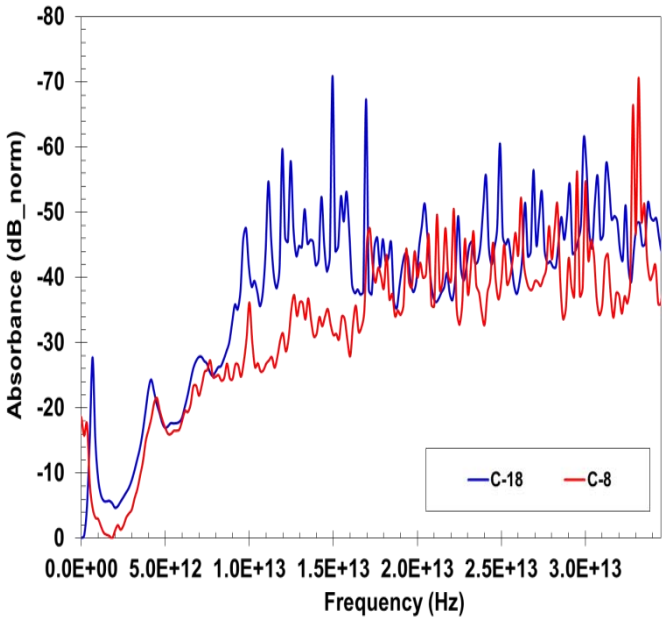


Fig. 10. The absorbance spectra of two SAMs on silicon wafer. Several peaks may be identified for characteristic differences between the two SAM species.

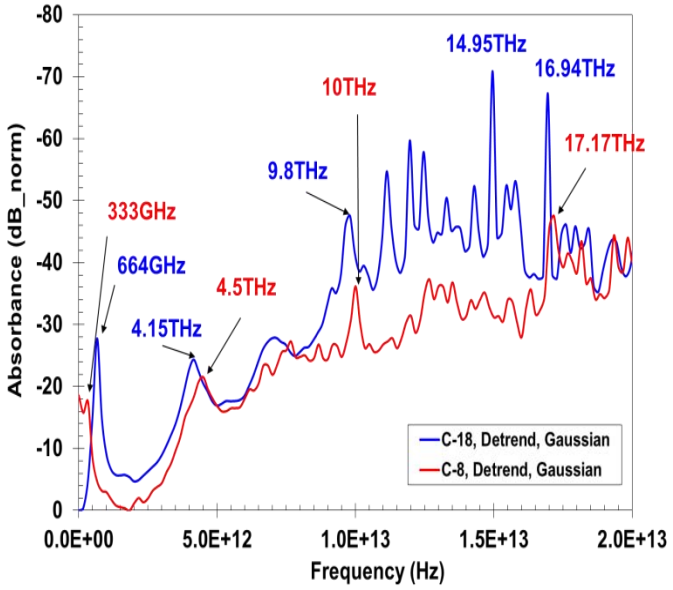


Fig. 11. The absorbance spectra of both SAMs (same as Fig. 10, but X-axis truncated to 20 THz). Several peaks may be identified for characteristic differences between the two SAM species.

## REFERENCES

[1] Rahman, Anis., Dendrimer Based Terahertz Time-Domain Spectroscopy and Applications in Molecular Characterization. Journal of Molecular Structure, 2011. 1006: p. 59-65.

[2] A. Rahman, S. Frenchek, B. Kilfoyle, L. Patterkine, A. K. Rahman, and B. Michiniak-Kohn, "Diffusion kinetics and permeation concentration of human stratum corneum," Drug Development & Delivery, May 2012, pp. 43–49.

[3] A. Rahman and A. K. Rahman, "Wide Range Broadband Terahertz Emission From High χ(2) Dendrimer," in Terahertz Technology and Applications V, edited by Laurence P. Sadwick, Créidhe M. O'Sullivan, Proc. SPIE Vol. 8261, 82610H (2012).

[4] "Investigation of self-assembled monolayers on silicon wafer by terahertz spectrometry," white paper: http://arphotonics.net/THzSpectraSAMonSiliconWafer.pdf.

[5] http://arphotonics.net/TeraSpectraBrochure_spec_2011_.pdf