Controlling TC SAW Filter Frequency with Picosecond Ultrasonics

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***Abstract* – PULSE™ technology is a first principles based acoustic metrology technique that is capable of measuring various parameters of interest in semiconductor manufacturing such as multi-layered metal thickness, sound velocity of dielectric films and reflectivity. In this paper, we demonstrate the applications of PULSE technology in the TC-SAW process; to control TC-SAW filter frequency which is dependent not only on IDT line spacing but also on its thickness and sound velocity of dielectric layer that is surrounding IDT. Additionally, we also demonstrate that the technology can be used to detect unwanted residual passivation layer on UBM to capture process excursion for corrective action in an early stage.**

Keywords: picosecond ultrasonics, metrology, TC-SAW filter, IDT, frequency, reflectivity

I. INTRODUCTION

Rapid growth of the mobile device, automotive and IoT markets require a strong demand for various acoustic filters at different frequencies. While the high-end communication market is shifting from 4G to 5G, demand for lower frequency surface acoustic wave (SAW) filters is still growing with increased communication through Wi-Fi, LTE, GSM, Bluetooth, etc. They are attractive for their relative ease of manufacture and their filtering characteristics which are almost completely controlled by device design. The main drawback of these devices is the temperature instability of filters and resonators. This is a function of the temperature coefficients of elasticity (TCE), coefficients of thermal expansion (CTE) and the CTE's effect on density. Due to narrow bandwidth requirements, process control for each filter's manufacturing becomes tighter than any other semiconductor process. To meet the very tight requirement of acoustic filter process control, manufacturers need metrology tools to meet the stringent requirements for repeatability and accuracy. Picosecond Ultrasonic (PULSE) technology is a proven metrology for the measurement of metal film thickness. Capability for measuring sound velocity of transparent and semi-transparent films is also well established. In an earlier paper, we described how the technology was adopted for characterizing single crystal piezoelectric materials [1, 2].

The frequency of a SAW filter is known to be determined mainly by the spacing of fingers in inter-digital transducer (IDT). The spacing determines the wavelength of the surface wave produced by IDT and its frequency is inversely proportional to the wavelength [3]. However, IDT spacing is not the only factor that determines the frequency of the SAW filter. In this paper, we will show that TC-SAW (temperature-compensated surface acoustic wave) filter frequency is also dependent upon IDT thickness and sound velocity of silicon dioxide (SiO_2) that is surrounding the IDT. We also report how we can measure metal film thickness of IDT and sound velocity of silicon dioxide (SiO_2) to control the frequency of TC-SAW filter devices. This will demonstrate that accurate and repeatable metrology for IDT thickness and SiO_2 sound velocity is inevitable for the frequency control of TC-SAW devices and Picosecond ultrasonic technology (PULSE) meets the requirement of TC-SAW process control. We also report on how the technique has been utilized for detecting incomplete removal of the passivation layer on under bump metallization (UBM) that can result in serious problems during downstream testing/processing in the form of poor electric connection or bonding with another chip. Typically, any residual dielectric layer left behind is thin and transparent, making its detection with automated optical inspection (AOI) practically impossible. Using the PULSE technology, we demonstrate that during measurements of the UBM, we can flag the existence of residual dielectric film as it causes noticeable change in the intensity of reflected probe beam. We also show that this intensity change has a very good correlation to the residual layer thickness and the method provides a means for indirectly determining the thickness of the residual layer.

II. METROLOGY OPTIONS

The standard protocol that was implemented in the fab was blanket wafer measurements; measurements of dielectric films using ellipsometers or reflectometers. Information needed was obtained in a tedious, time-consuming manner using a combination of methods using off-line techniques. Measurements on a product wafer as well as characterizing within wafer uniformity profiles were not possible in some of these systems that were available to us. We had identified that there were three critical information that we would like to obtain with minimum number of metrology tools or steps. They were a) simultaneous measurement of multi-layer metal stacks, b) sound velocity measurement of oxide, and c) residual nitride detection. With the introduction of the PULSE technology, our intent is to achieve all these measurements with one technology.

In the following sections we describe the experimental set up used on the samples and summarize results from the application of the technique to not only characterize the thickness of the films but also its effectiveness in detecting the presence of residual layer.

III. METHODOLOGY

A. *Measurement of Metal Thickness*

Picosecond ultrasonic technology (PULSE) is a non-contact, non-destructive pump-probe laser acoustic technique that can be used for the measurement of film thickness [4]. It is a proven workhorse in semiconductor fabs around the world since it was introduced in late 1990s. We have previously discussed how the technology is used for measuring metal films and also for characterizing dielectric films, in the presence of a metal transducer layer [2, 5].

B. *Measurements of Reflectivity*

In addition to measuring thickness, we also have the ability to measure the change in reflectivity of the film at the measurement site. The change in surface reflectivity caused by the returning acoustic wave is typically a millionth of its nominal reflectivity. For metal films, which are much thicker than their absorption length, reflectivity is mostly insensitive to thickness variation. For thin films, however, reflectivity tends to be sensitive to thickness variation due to interference effect. Therefore, reflectivity measurement provides a novel and efficient way of detecting unwanted residual films on thick metal.

IV. RESULTS

A. *Characterization of IDT*

Shown in Fig. 1 is the change in reflectivity as a function of time from measurement of IDT film on a product wafer. The large minimum seen at ~110ps corresponds to the returning echo (round trip travel time) from the IDT layer. We can calculate the thickness of the film, using a known speed of sound in the material and the echo time. The thickness is calculated to be ~2700Å. Typical repeatability (3σ) for the measurement is ~0.15Å.

The data used in this study was collected on actual device wafers. The wafers were fully processed and the frequency for each chip was measured as a final step in the process. The measured frequency was used to derive correlation with PULSE measurements.

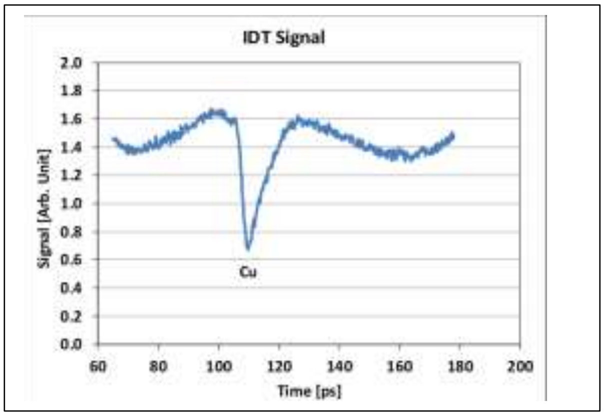

Fig. 1. Raw signal of reflectivity change versus time measured on IDT metal. Large negative peak at ~110ps corresponds to the round trip travel time through the film.

Fig. 2 shows the correlation between the frequency of TC SAW filter and IDT thickness. IDT thickness was measured after the deposition process and the frequency of the same device characterized. Absolute values are not shown to protect the confidentiality, but one can readily see that the filter frequency decreases by ~ 0.14MHz when the IDT thickness increases by ~ 1Å. This demonstrates that the thickness of IDT needs to be controlled at Angstrom level to achieve the desired filter frequency in the final product. Therefore, the metrology tool used to monitor the thickness needs to meet stringent repeatability and accuracy requirements. The PULSE technology is also intrinsically matched and this is very critical for adoption in a high volume manufacturing.

Fig. 3 shows the raw signal of reflectivity change versus time for measurement of SiO_2 film over IDT in TC-SAW product wafer. Sound velocity of SiO_2 can be calculated from the period of the oscillations. Sharp positive peak at ~600ps is due to the acoustic wave reflection at the interface with IDT and corresponds to the round trip travel time of sound wave in SiO_2. Using the round trip travel time and velocity calculated from the period of the oscillations, thickness of SiO_2 can be calculated. The raw data shows excellent signal to noise and typical 3 sigma repeatability for thickness is ~ 4.5Å and for velocity 0.09Å/ps for SiO_2.

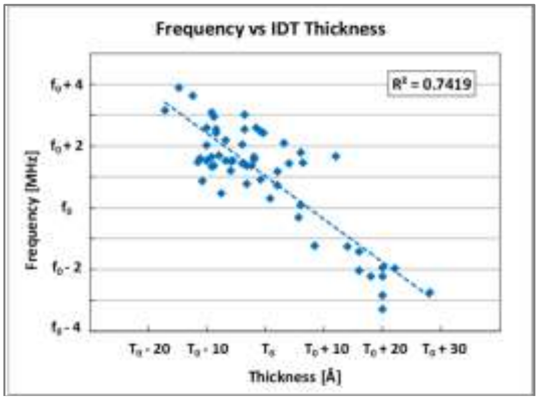

Fig. 2. Correlation between SAW filter frequency and IDT thickness.

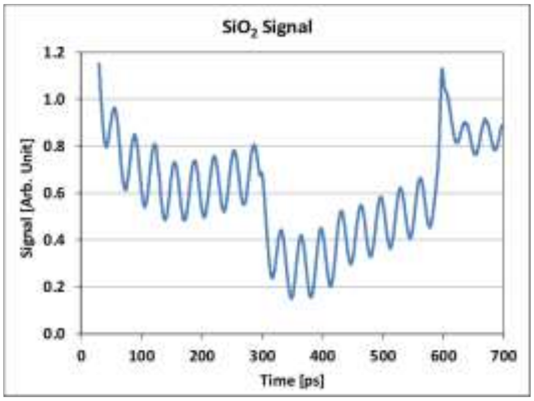

Fig. 3. Raw signal measured on Oxide on IDT. Sound velocity of SiO$_2$ can be calculated from the period of the oscillations in the signal.

Figure 4 shows the correlation between the frequency of TC SAW filter and sound velocity of SiO$_2$ that was measured after SiO$_2$ deposition process on the same filter. As with the previous data, absolute values are not shown. Nevertheless, one can see that filter frequency increases by about 2.8MHz when sound velocity of SiO$_2$ increases by 1Å/ps. This also clearly shows that the process needs to be tightly controlled to achieve the desired filter frequency in the final products and the metrology requirement for 3 sigma repeatability needs to be better than 3Å/ps.

B. Residual Film Detection

In Fig. 5, change in reflectivity versus time from measurements on a UBM is shown. This is a multi-layer Au metal stack. By fitting the measured signal with signal simulation SW, we can measure individual thickness of the multi-layer stack simultaneously. Typical repeatability of 3 sigma < 0.6% for each layer. The Au layer thickness of this stack is ~2500Å. Thickness changes in this film (within the process window), does not change the reflectivity of the film. However, if there is an incomplete removal of the SiN layer during the subsequent etch process, it results in a noticeable change in reflectivity. The presence of this residual layer does not manifest itself in the acoustic echoes from the multi-layer metal stack and hence monitoring just thickness only would not have flagged this misprocess. Also, the residual layer is very thin and is not detected using optical inspection techniques.

We attempted to correlate/quantify the reflectivity change as measured by the PULSE technology with the thickness of the residual SiN by using transparent film metrology. Shown in fig 6 is the correlation between reflectivity measured by PULSE technology and residual SiN thickness. We see an excellent correlation between the reflectivity change and the residual SiN thickness. A reflectivity value < 0.48 can be used as a flag for the existence of residual SiN on UBM. The correlation equation has been used to estimate the thickness of residual SiN and has also helped in the optimization and fine-tuning of the etch process.

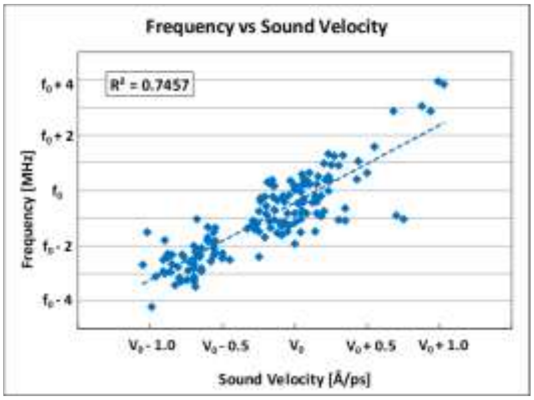

Fig. 4. Correlation between SAW filter frequency and sound velocity of SiO$_2$ that is surrounding IDT.

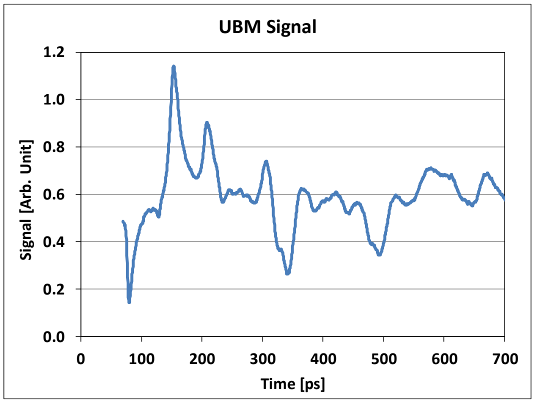

Fig. 5. Raw signal of reflectivity change versus time measured on UBM.

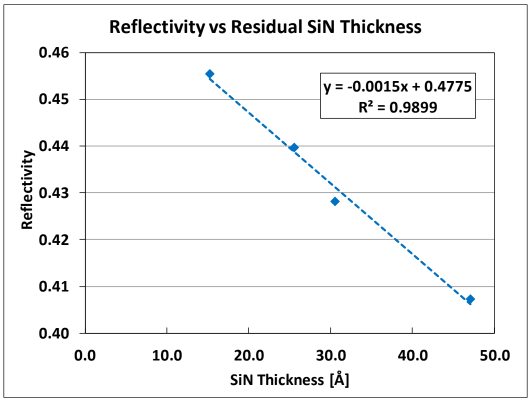

Fig. 6. Correlation between SiN thickness on metal pad and reflectivity.

V. CONCLUSION

As mentioned earlier, the acoustic filter market is expected to grow significantly in the coming years as the industry transitions to 5G. The advances in filter technologies will place stringent demands on manufacturing which in turn will require very accurate metrology techniques. The attractiveness of the said technology increases as more parameters critical for process monitoring and control are provided.

In this paper, we have demonstrated the application of the PULSE technology for characterizing the IDT thickness and sound velocity of SiO_2 on product wafers. The excellent repeatability (3 sigma < 0.15Å) and accuracy of the technique enabled measurements on product wafers and met the tight process control requirements. We have shown that the thickness of IDT and velocity of oxide are correlated to the central frequency and are critical to the performance of the TC-SAW filters. Adoption of the technology during research and development has helped improve the data turnaround times and provided information that was otherwise unavailable. In addition, we have shown that the existence of residual dielectric film on UBM can be detected for corrective action during in-line monitoring of the UBM thickness.

Future work will focus on combining metrology results with Discover® software data analytics and run-to-run (R2R) control of process tools for automatic process control (APC), thus enhancing the solution.

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