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# Very high aspect ratio through silicon via reflectometry

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## ABSTRACT

Through Silicon Via (TSV) technology is a key feature of new 3D integration of circuits by creation of interconnections using vias, which go through the silicon wafer. Typically, the highly-selective Bosch Si etch process, characterized by a high etch rate and high aspect ratio and forming of scallops on the sidewalls is used. As presented in this paper, we have developed an experimental setup and a respective evaluation algorithm for the control and monitoring of very high aspect ratio TSV profiles by spectroscopic reflectometry. For this purpose square via arrays with lateral dimension from 3 to 10  $\mu\text{m}$  were fabricated by a Bosch etch process and analyzed by our setup. By exploiting interference and diffraction effects of waves reflected from the top and bottom surfaces as well as from the side walls of the TSV patterns, the measurements provided etch depths, CD values and scallop periods. The results were compared with data obtained by a commercial wafer metrology tool. Aspect ratios of up to 35:1 were safely evaluable by our setup.

**Keywords:** spectroscopic reflectometry, through silicon via (TSV), Bosch etching process, etch depth, scallop size

## 1. INTRODUCTION

Through Silicon Via (TSV) technology is a key feature of new 3D integration of microelectronic devices. Generally, TSVs are formed by etching a vertical via and filling them with a conductive material, such as copper [1]. TSV technology has opened up new possibilities of 3D integration of micro-electro-mechanical systems (MEMS), photonic circuits, microfluidic devices, or electrical grounding of CMOS and BiCMOS devices [2-3]. The very high aspect ratio (AR) (via depth/via size > 10:1) opens up potential of smaller packaging, stress reduction, and low costs for advanced 3D integration. It is further advantageous in terms of reduction of bending stress effects by wafer thinning and thermal stress inside the TSV by mismatch of thermal expansion of Si and the filling material [4-5].

Via etching is a critical step in TSV integration impacting isolation, metallization and wafer thinning. Typically, the Bosch process is used for this purpose, providing high selectivities and high etch rates required for high AR deep silicon etching [6]. The Bosch process includes repeated alternating isotropic dry etching and sidewall passivation / deposition steps. In this way a series of scallops are generated on the sidewalls which may reduce the reliability of the devices, appearing as leakage currents, thermo-mechanical stress or slow device response.

The etch profile including the scallop size needs to be monitored and well controlled to ensure all requirements for 3D interconnects. Usually, secondary electron microscopy (SEM) cross-section image analysis is applied. But SEM is destructive, time consuming and depends on the cutting technique. Optical interferometry and reflectometry are the main nondestructive metrological methods for this purpose [7, 8] but their use is limited by smaller dimension and high AR due to the requirement of obtaining a measurable signal of reflected light from the bottom of the TSV.

Via structures with AR of more than 10:1 and patterns with lateral dimensions in the range below 5  $\mu\text{m}$  remain a challenge. In our previous papers [9-11], the inspection of the TSVs depth and critical dimensions of their opening was performed nondestructively by an industrial thickness measurement tool (KLA-Tencor Spectra Fx200) using UV-VIS spectral reflectometer. It was shown that spectral reflectometry can be used for the monitoring of geometrical parameters of TSVs with dimensions starting at 3  $\mu\text{m}$  and AR up to 17:1 [11], where our own evaluation software was used.

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In this paper we will present our own experimental setup (DeepView) and a respective evaluation algorithm for the control and monitoring of TSV profiles with very high ARs (up to 35:1) by spectroscopic reflectometry. The results will be compared with data obtained by the commercial wafer metrology tool. The limiting factors of optical TSV depth measurements will be discussed, as well as further improvements.

## 2. EXPERIMENTAL

Square via arrays with lateral dimensions from 3 to 10  $\mu\text{m}$  were fabricated by a highly selective Bosch etch process: isotropic dry etching with sulfur hexafluoride ( $\text{SF}_6$ ) and sidewall passivation by polymer deposition with octafluorocyclobutane and oxygen ( $\text{C}_4\text{F}_8/\text{O}_2$ ), by the Tegal 200 (SPTS) tool. Vias depth of up to 60  $\mu\text{m}$  by using a photo resist as an etch mask and up to 160  $\mu\text{m}$  by using a 3  $\mu\text{m}$  thick  $\text{SiO}_2$  hard mask were achieved.

All measurements were carried out by DeepView reflectometry setup depicted in Figure 1. It consists of a 100  $\mu\text{m}$  multimode optical fiber Y-cable for reflection with linear spectrometer end, condenser and focusing objective with variable aperture. Objectives with low numerical aperture (NA) from 0.1 to 0.01 and three spectrometers with wavelengths resolution of  $\sim 0.5$ , 1 and 1.6 nm were used. The wavelength range was 400–800 nm. The results of our setup were compared with data of commercial wafer metrology tool KLA-Tencor Spectra Fx 200 [9-11] with NA=0.01, where our own evaluation algorithm was applied.

TSV depth was extracted from the interference effect between waves reflected from TSV's top and bottom surfaces using Fourier (FFT) analysis. Scanning electron microscopy (SEM) inspections were used in order to verify our results.

## 3. RESULTS AND DISCUSSION

Figure 2 and 3 show two examples of SEM views of the investigated TSV array structures. The SEM view in Figure 2 shows TSV array structures with AR of 13:1 prepared by using the photo resist as an etch mask. Figure 3 shows TSV structures prepared by an etching process with 3  $\mu\text{m}$   $\text{SiO}_2$  hard mask in order to receive very high AR of about 30:1. Two types of surface texture can be observed on the TSV side walls. The first type is the scalloping effect which is caused by the alternating isotropic etch and passivation steps in the Bosch process. The second type is a random sidewall roughness due to the ion behavior during etching. Sidewall scalloping occurs primarily in the top region where scattered ions have wide trajectories, and decreases with depths where ion trajectories are more restricted. The effect of random sidewall roughness is much more characteristic for very high AR TSV's.

The reflection spectra for 5  $\mu\text{m}$  TSV array structures measured by different setups are presented in Figure 4a. The reflectance spectra oscillate at distinct frequencies over the wavelength range of  $\sim 400$ –1000 nm. The high frequency oscillations are due to interference effects between the reflected waves from the top and bottom surfaces of the TSV structures, whereas the low frequency oscillation for  $\lambda_r \sim 500$  nm is caused by the scallop diffraction effect as described in [10]. For the back-diffraction to the sensor the scallop period is calculated as  $g \sim \lambda_r/2$ . Figure 5 shows the Fourier signals of the reflection spectra in Figure 4. Whereas a very distinct Fourier peak was achieved from our spectrum, the corresponding peak of the spectra obtained by the commercial system was significantly weaker and appears to be rather close to the detection limit. Figure 6 shows the reflection spectra of the samples with the maximum hole depth, achievable by our etch process. They demonstrate the limitation of our present setup. Whereas hole patterns of 120  $\mu\text{m}$  depths could be still easily detected for CD values of 5  $\mu\text{m}$ , in the case of CD values of 3  $\mu\text{m}$  the detection limit seems essentially achieved at depth values around 110  $\mu\text{m}$ . The commercial system did not allow any depth evaluation, however, the scallop diffraction effect is indicated by a broad intensity maximum around 530 nm for CD values in accordance to our reflection signal.

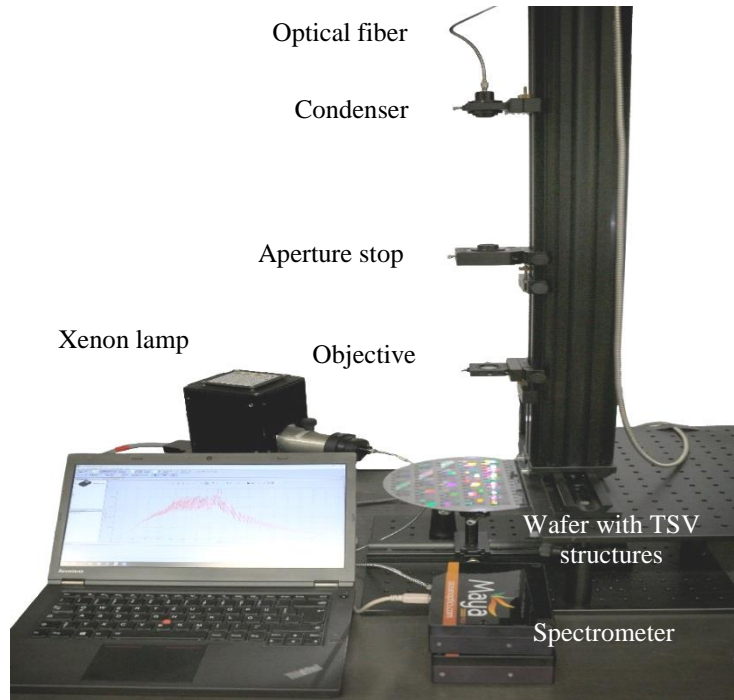


Figure 1. DeepView-setup consisting of a multimode fiber bundle including condenser and focusing objectives with variable aperture.

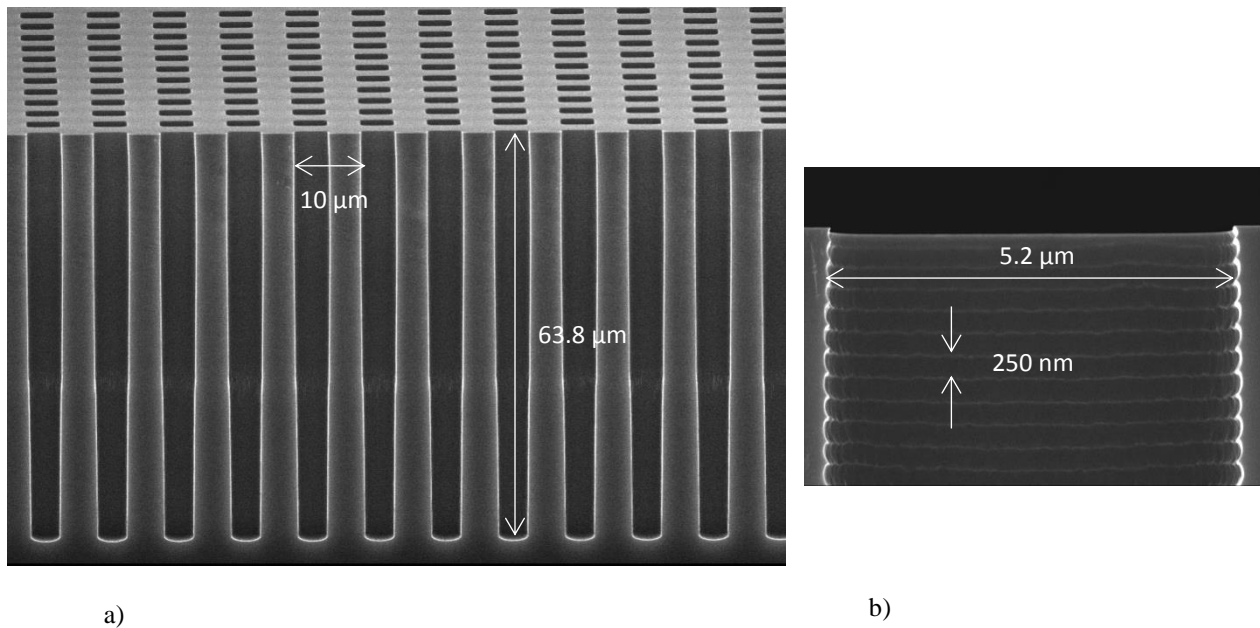


Figure 2. Cross-section SEM views of TSV array with CD  $\approx 5.2 \mu\text{m}$ , period =  $10 \mu\text{m}$ , and depth  $\approx 64 \mu\text{m}$  (a), top region with a scallop period of 250 nm (b).

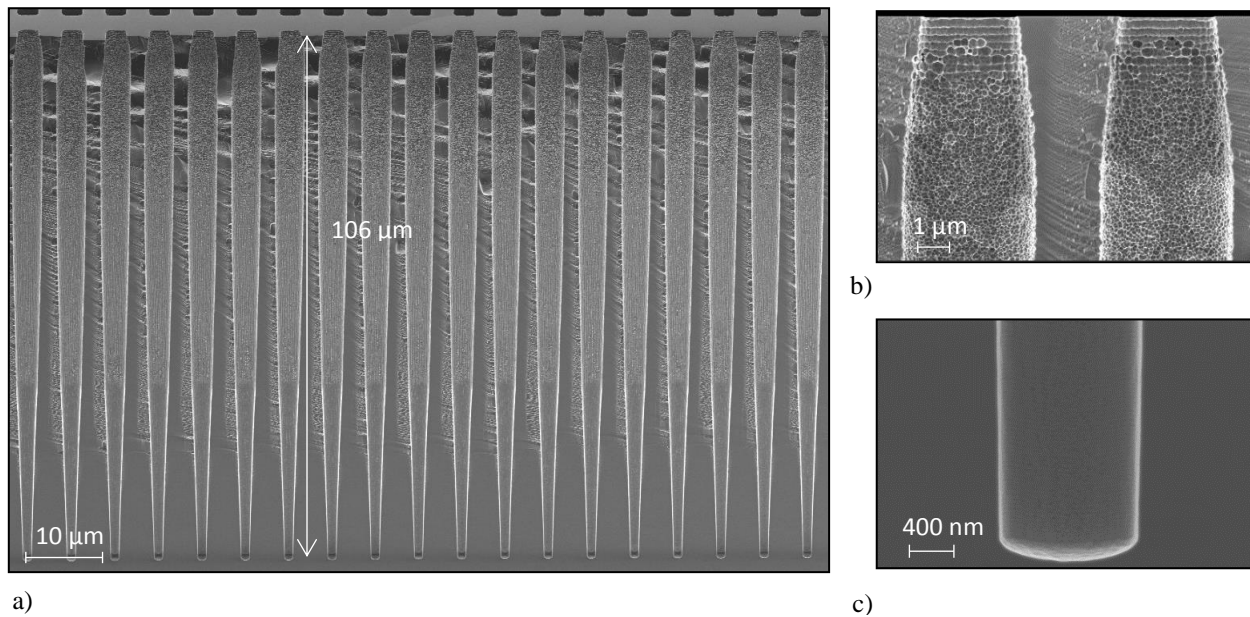


Figure 3. Cross-section SEM views of TSV array with CD  $\approx 3 \mu\text{m}$ , period =  $6 \mu\text{m}$ , and depth  $\approx 100 \mu\text{m}$  (a), top (b), and bottom (c) region.

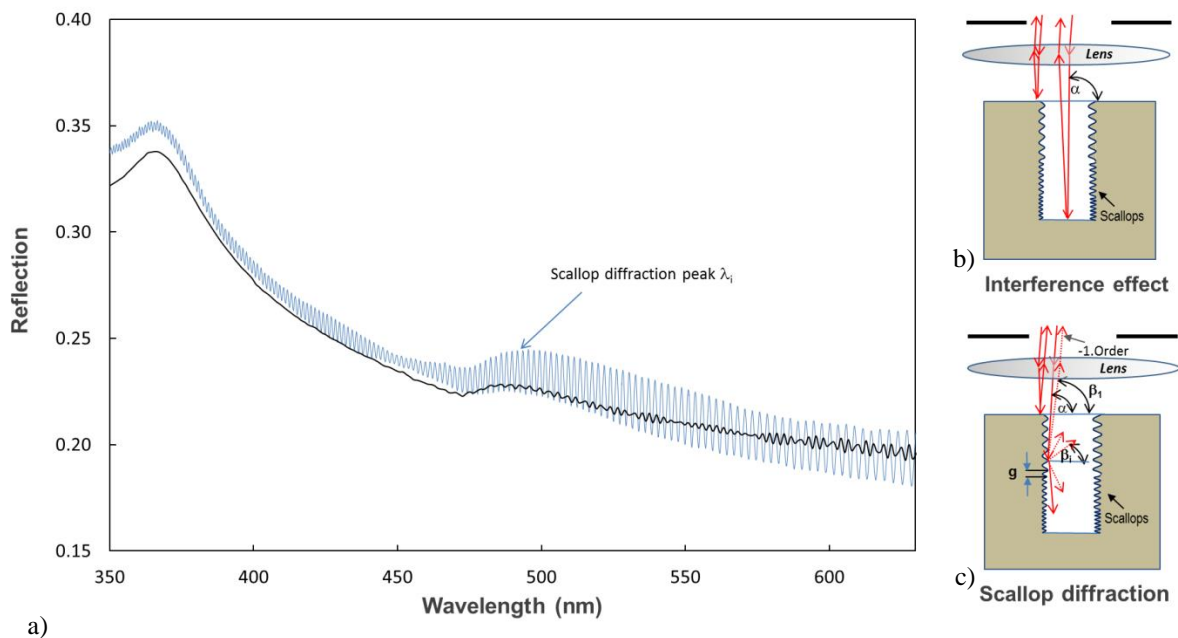


Figure 4. Reflection spectra of  $5 \mu\text{m}$  CD and  $10 \mu\text{m}$  pitch TSV arrays with an etch depth around  $60 \mu\text{m}$  shown in Figure 2 (**Blue** – DeepView-setup with  $\text{NA}=0.01$ , spectral resolution  $\sim 0.5 \text{ nm}$ , **Black** - KLA Tencor Spectra Fx 200) (a) and schematic representation of interference (b) and diffraction (c) effects, where  $\alpha$  is the angle of incidence and  $\beta_i$  is the diffraction angle of diffraction order  $i$ , depending on the scallop period  $g$ .

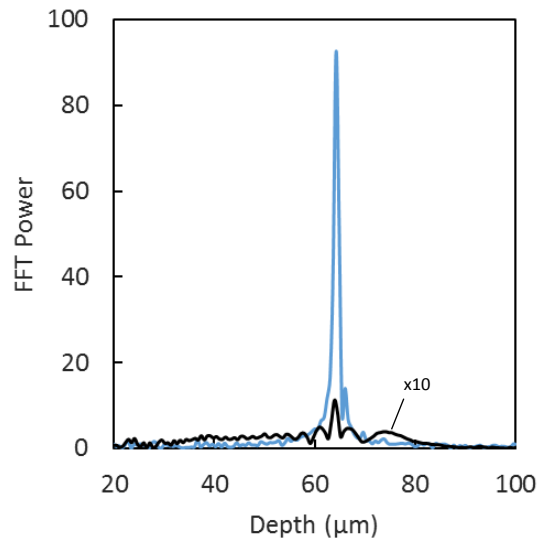
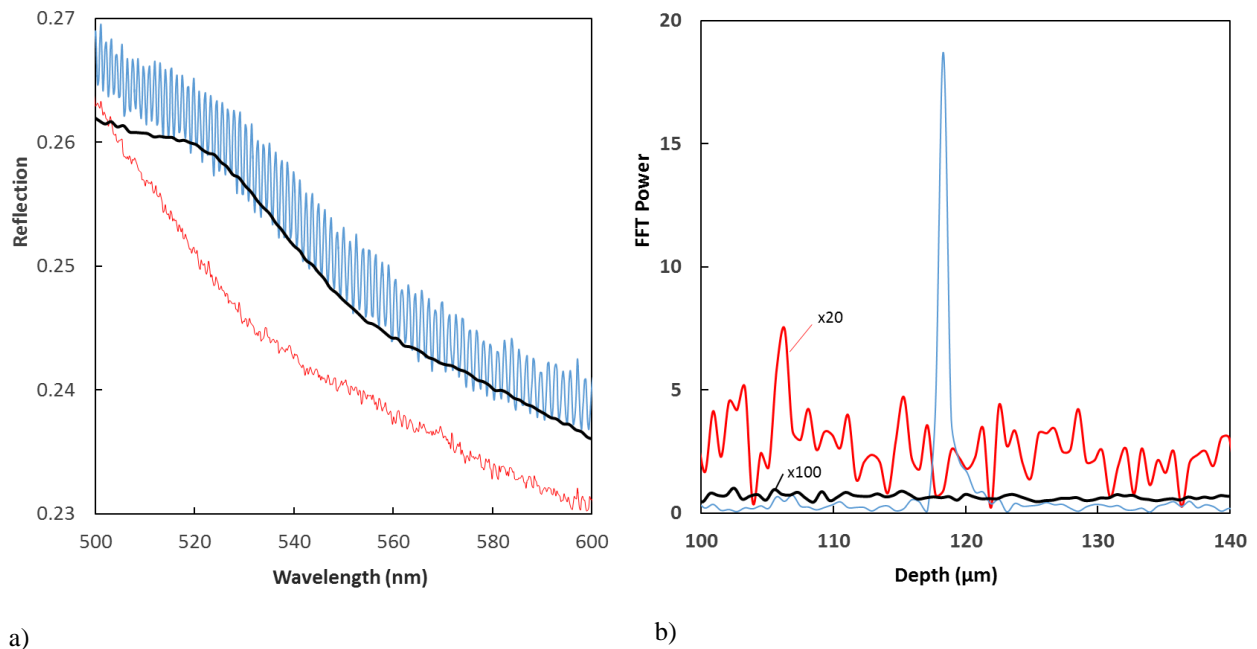


Figure 5. Fourier-spectra for the etch depth evaluation (**Blue** - DeepView-setup with NA=0.01, spectral resolution  $\sim 0.5$  nm, **Black** - KLA Tencor Spectra Fx 200).



a)

b)

Figure 6. Reflection spectra (a) and Fourier spectra (b) for 5  $\mu\text{m}$  CD and 10  $\mu\text{m}$  pitch TSV arrays with an aspect ratio of 24 (**Blue**, **Black**) and for 3  $\mu\text{m}$  CD and 6  $\mu\text{m}$  pitch TSV arrays with an aspect ratio of 35:1 (**Red**) produced using hard mask etching (**Blue**, **Red** - DeepView-setup with NA=0.01, spectral resolution  $\sim 0.5$  nm and **Black** - KLA Tencor Spectra Fx 200).

The TSV depth was determined by applying our own Fourier based algorithm to the normalized reflection spectra. The observed spectral range was from 350 to 630 nm. According to Figure 6 our system is currently limited to aspect ratios of about 35:1 in the case of CD values of 3  $\mu\text{m}$ .

The main limiting factors of the TSV depth measurement are the coherence length and the numerical aperture. The coherence length  $\Delta l$  at a given wavelength  $\lambda$  can be determined by  $\Delta l = \lambda^2 / \Delta \lambda$ , where  $\Delta \lambda$  is the transmission line width (resolution) of the spectrograph. In order to receive a good interference contrast (IC),  $\Delta \lambda$  should significantly exceed  $2d$ , where  $d$  is the via depth. In the case of high aspect ratios the NA of the optics is a second important parameter. If the NA is significantly larger than  $CD/2d = 1/2AR$ , the vast part of the detected light is due to reflections at the top wafer surface. Due to the strongly unbalanced top and bottom reflections the IC would be small in this case. For this reason as a practical rule it should hold  $NA < 1/2AR$ .

In order to receive a quantitative value for the quality of the depth measurement, we define the goodness-of-fit (GOF) by using the correlation function of measured and calculated reflection, known as Pearson Correlation Coefficient (PCC) and the signal to noise ratio (SNR) of the Fourier depth analysis, defined as the ratio of the amplitude of the FFT-main power peak to the mean noise amplitude of the FFT-power function.

As seen in Figure 7a the SNR value strongly depends on the IC value. For small IC values below 1% the SNR increases nearly exponentially with IC. The corresponding PCC function in Figure 7b shows a similar behavior. A good correlation of PCC and SNR values (Figure 7c) suggests that both PCC and SNR analysis are similarly adequate for quality analysis. Figure 8a, b show experimental SNR values as a function of the numerical aperture and spectral resolution, respectively, which demonstrate the strong influence of both parameters.

Figure 9 shows the PCC as a function of aspect ratios at  $NA = 0.01$  and  $\Delta \lambda = 0.5$  nm, suggesting that our setup can handle aspect ratios of up to 35:1.

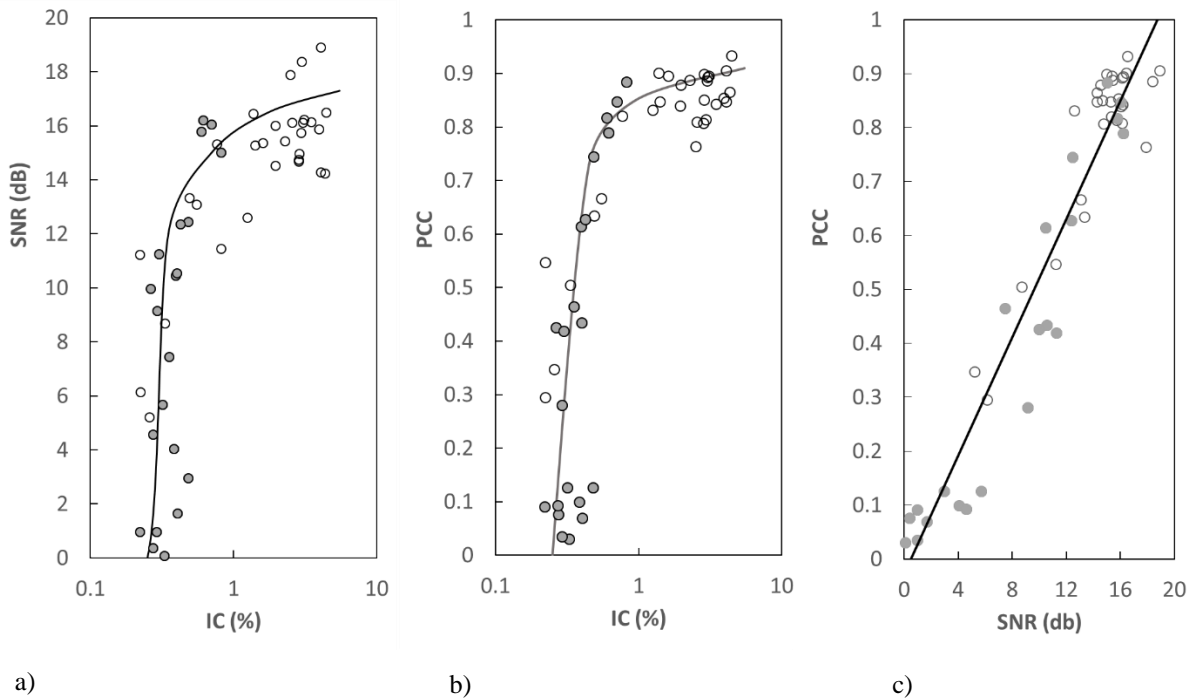


Figure 7. Evaluation parameters SNR (a) and PCC (b) vs. the reflection modulation (interference contrast IC), and their correlation (c) for 3, 5 and 10  $\mu\text{m}$  square via arrays produced with resist ( $\circ$ ) and hard mask ( $\bullet$ ) by Bosch etch process and measured with different NA ( $0.01 \leq NA \leq 0.1$ ) and the spectral resolution of 0.5 nm.

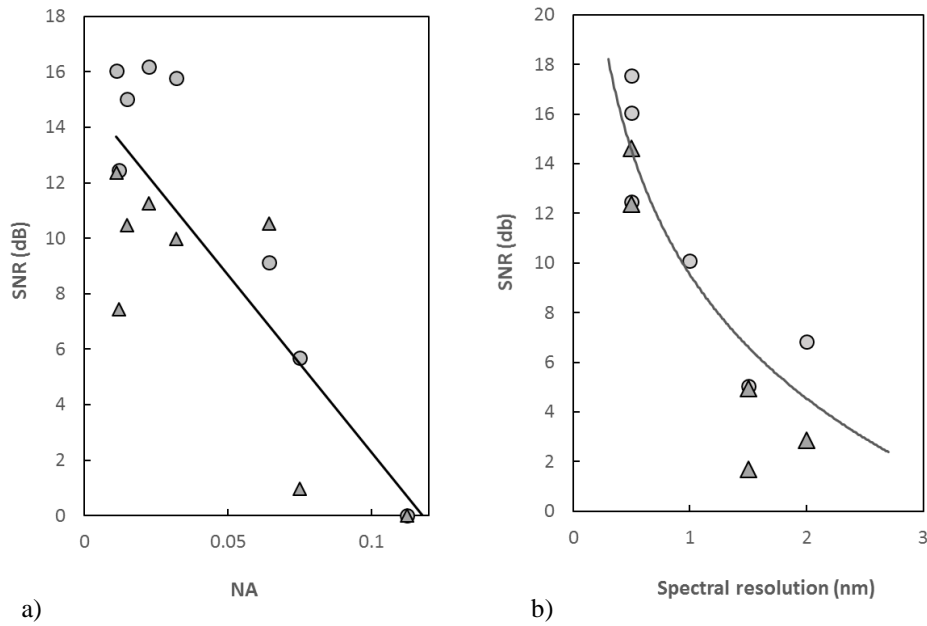


Figure 8. SNR of the FFT-power peak for 5 μm (○) and 10 μm (Δ) square via arrays with aspect ratios of 15:1-25:1 etched with hard mask. a) SNR vs. NA with the spectral resolution of 0.5 nm, b) SNR vs. spectral resolution with NA=0.01.

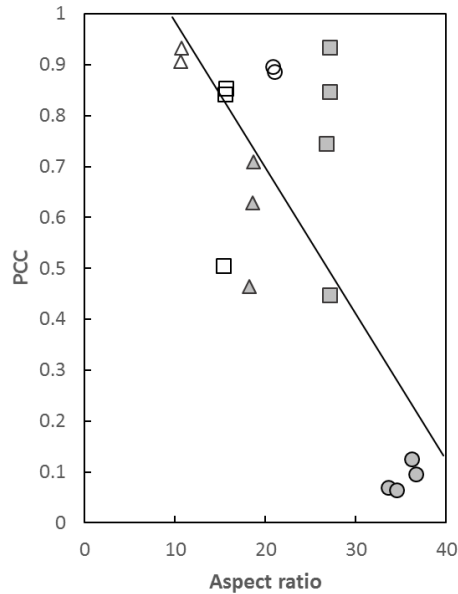


Figure 9. Pearson correlation vs. aspect ratio of 3(○), 5(□) and 10(Δ) μm square via arrays produced with resist mask and 3(○), 5(□) and 10(Δ) μm square via arrays produced with hard mask by Bosch etch process and measured with NA=0.01 and the spectral resolution of 0.5 nm.



## 4. CONCLUSION

We have developed a setup for the depth determination of very deep silicon vias, based on spectroscopic reflectometry. Besides the depth measurements, the scallop period, generated by the gas exchange etch process, could be derived from the sidewall diffraction effects. The depth determination was performed by own Fourier based evaluation algorithm. Pearson correlation coefficients between measured and calculated reflection as well as signal to noise ratio considerations of the Fourier spectrum were introduced as reliable quality check of the measurements, providing the limitations of the setup in terms of depth and CD values of the vias.

Using our setup, the reflection data for patterns with aspect ratios of up to 35:1 were safely evaluable, whereas a reference commercial metrology tool was limited to aspect ratio of up to 17:1. We believe that significantly higher aspect ratios should be detectable by improving numerical aperture and spectral resolution of our setup.

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