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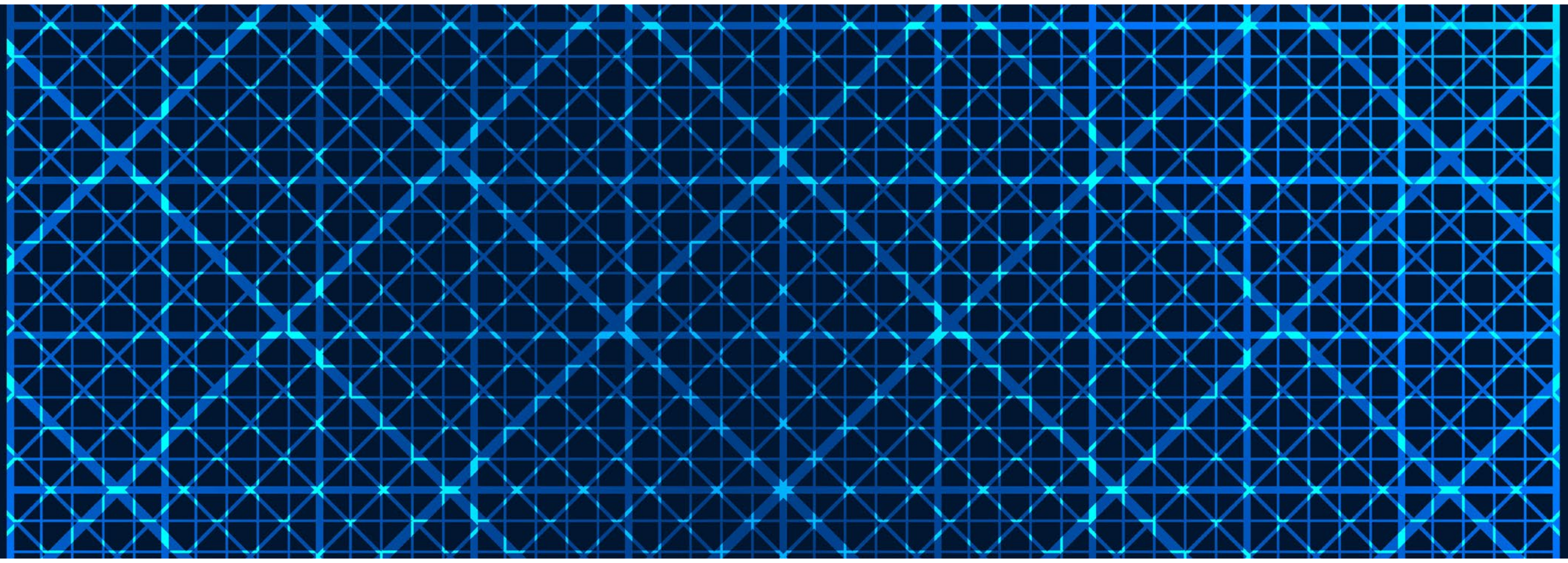
METROLOGY



Precise thickness measurements of thin SiO_2 mask films

We study the optical properties of QDs that are embedded in PhC cavities (Figure 1a), leading to enhanced emission (the Purcell effect), or in WGs (Figure 1b), producing photon multiplexing devices. A typical device is fabricated from a multi-layer GaAs/$Al_{0.7}Ga_{0.3}As$/GaAs epitaxially grown stack, where the top 250 nm thick GaAs layer contains the active part of the device, and the 1 µm $Al_{0.7}Ga_{0.3}As$ sacrificial layer is eventually etched away to produce a floating membrane device. This membrane contains one or several 20 nm $In_{0.3}Ga_{0.7}As$ QDs in specific positions, and an etched PhC structure (large array of 100 nm holes, with several holes missing in a specific configuration), precisely aligned with the QDs. These devices require accuracies of 1-20 nm in several processing steps, so they all involve high-performance electron-beam lithography. To withstand wet or plasma (ICP) etching of GaAs, we have to use a hard SiO_2 mask, to which the lithography pattern is transferred by dry etching (RIE). The accuracy of this transfer depends on knowing the precise thickness of the mask layer. As the SiO_2 layer is 40-80 nm thick, we need 1 nm precision in this measurement. The purpose of this study is to obtain high-precision (1 nm) measurements of thickness of thin (40-80 nm) SiO_2 films used as hard masks.

EPFL The Laboratory for Physics of Nanostructures (LPN) belongs to the Institute of Physics (IPYS) at the Ecole Polytechnique Fédérale de Lausanne (EPFL), one of the leading Swiss technical universities. Our main study is photonic nano-devices, based on the integration of position- and energy-controlled semiconductor quantum dots (QDs) with photonic crystal (PhC) optical cavities and waveguides (WGs). Led by Prof. Eli Kapon, all experimental issues are supervised by Dr. Benjamin Dwir.

EPFL

So far, only a stylus profilometer could be used on a daily basis to measure the SiO_2 mask thickness, and this was after a global calibration using calibration standards and a Sopra GES 5E spectroscopic ellipsometer in another laboratory. However, profilometry demands the wet etching of a "step" in the SiO_2 layer, so it is time consuming and not practical when full wafers are processed. Moreover, typical noise in profilometry is 5 nm RMS, so a lot of averaging is needed to obtain the required 1 nm accuracy (Figure 2a).

We now use the 3D optical profilometer S neox in its spectroscopic reflectometry mode as a quick and easy way to measure SiO_2 layer thickness. Using simple GaAs as a reference, we obtain 1 nm accuracy using this technique, which takes seconds to perform.

Measurements

Using a bare GaAs substrate as reference, we first measured the reflectivity spectrum of SiO_2 layers on GaAs using the built-in single-layer model. As seen in Figure 2b, the resulting reflectivity spectrum is very flat, showing no oscillations typical of thicker ($d>\lambda$) films. Still, the model fit is very good, giving the film thickness (84 nm) with 1 nm accuracy. The same type of measurement is shown in Figure 3, where a 38 nm film is measured.

In the case of the GaAs membrane structures, we have a 3-layer (SiO_2/GaAs/$Al_{0.7}Ga_{0.3}As$) structure on the GaAs substrate. In such cases, we enter this full structure into the model, still using GaAs as a reference. As a first test, we measure the reflectivity of the bare semiconductor multilayer structure without SiO_2. The resulting spectrum (Figure 4a) shows a good fit, producing the correct (verified by X-ray diffraction) GaAs and $Al_{0.7}Ga_{0.3}As$ layer thicknesses, as well as zero thickness for the top SiO_2 layer in the model. This time the reflectivity curve shows the typical oscillations, as usually appears in thicker ($d>\lambda$) layers.

Once we verified the bare semiconductor, we measured another sample, which was coated with SiO_2(Figure 4b). The resulting spectrum fit showed not only the semiconductor layers' thicknesses, but the correct SiO_2 layer's thickness (79 nm) as well.

As a final test, we tried to measure a sample coated with both SiO_2 and PMMA layers (Figure 4c). This time, the spectrum showed more complex oscillations, and the model fit was not as good as in the previous cases. Still, the fitted values were correct, showing this method's power and speed.

We have checked the values obtained with this method using both stylus profilometer and the Sopra GES 5E spectroscopic ellipsometer as controls, as well as with commercial calibration standards (SiO_2 layers on Si, from Micromasch), and found that the Sensofar system gives an accuracy of 1 nm, which is what we need.

Although we have shown very good results using multi-layer fitting, whenever possible we try to fit a model where we can fix all known parameters (e.g. semiconductor layer thicknesses) and vary only the top layer's thickness (usually SiO_2).

Conclusions

In order to process complex photonic nanostructure devices, we need high-accuracy (1 nm), fast thickness measurements of thin (usually < 100 nm) SiO_2 layers deposited on top of GaAs or multi-layer semiconductors. To this end, reflective spectroscopy provided by the S neox 3D optical profilometer from Sensofar was the perfect tool, providing the high accuracy, high measurement speed, and ease of use that we needed.

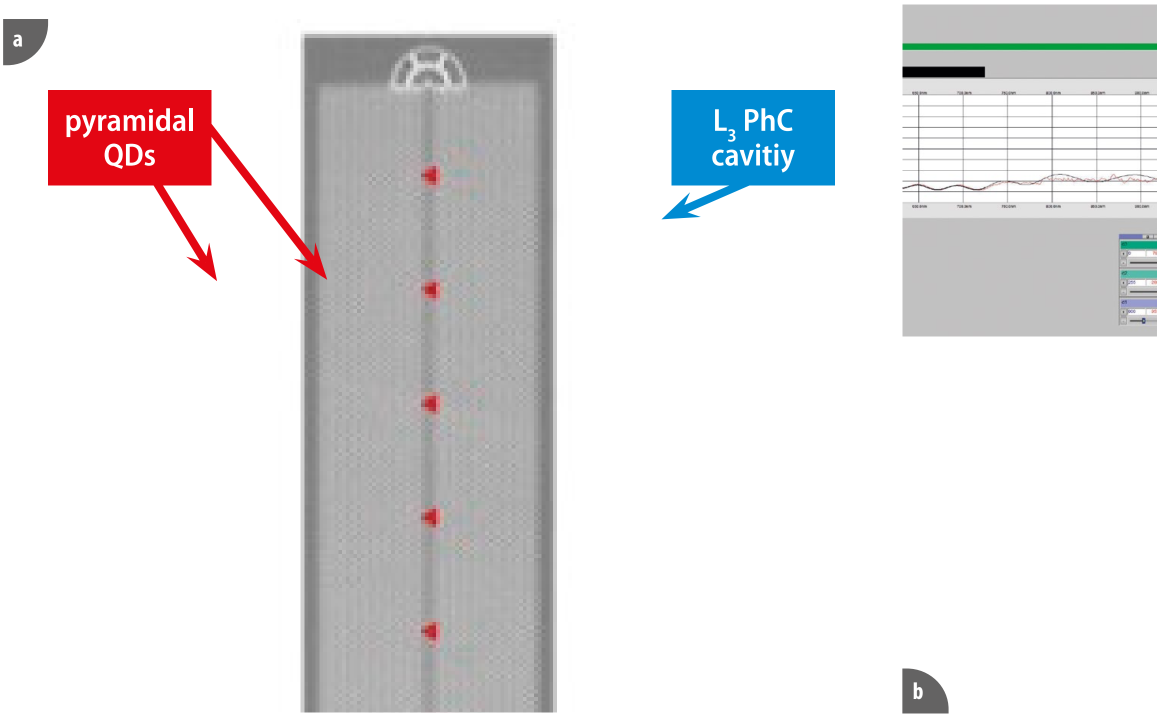
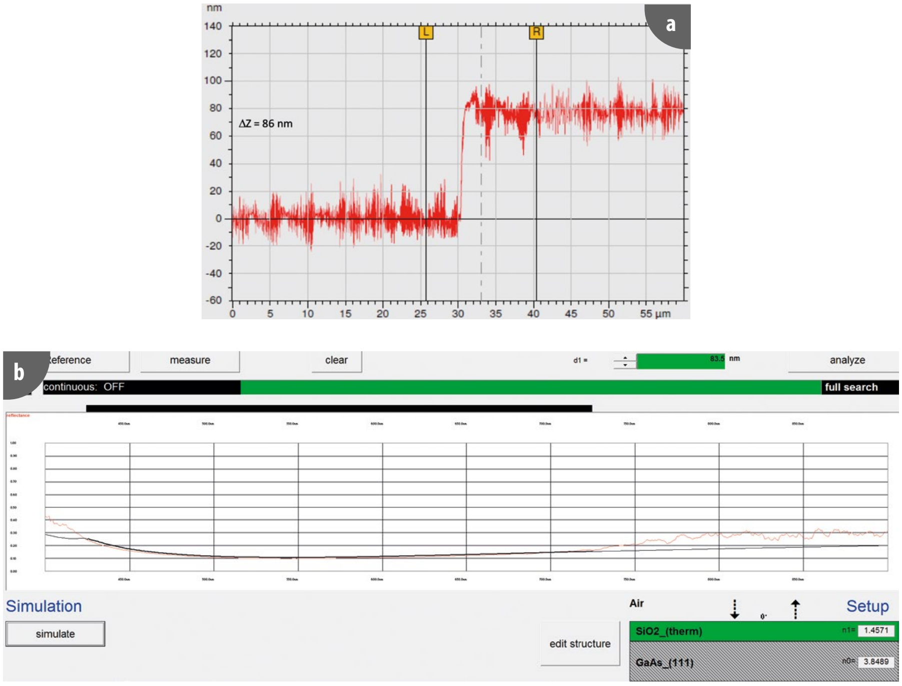


Figure 1.a) *SEM image of a network of QDs (darker spots) embedded in coupled L3PhC cavities.* **b)** *SEM image of PhC waveguide with an out-coupler at the top, containing six QDs (indicated by red triangles).*



d1 = 83.5 nm

n1= 1.4571

n0= 3.8489

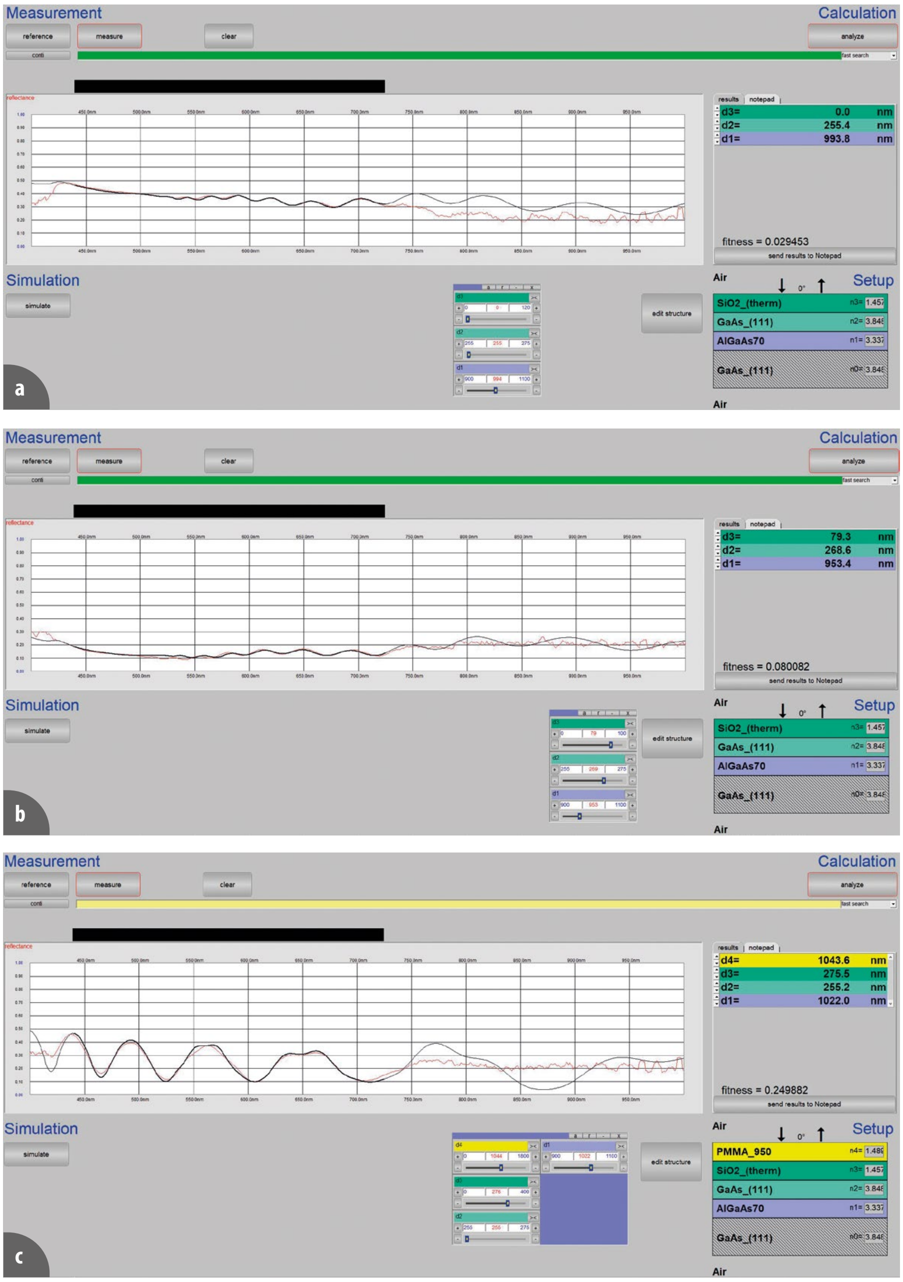
Figure 2.a) *Stylus profilometer trace of a step in the thin SiO_2 film.*
b) *Reflectivity spectrum of the same film, with model fit showing the thickness (84±1 nm).*

d1 = 37.9 nm

n1= 1.4571

n0= 3.8489

Figure 3. *Reflectivity spectrum of a thin SiO_2 film,*
with model fit showing the thickness (38±1 nm).



a)

d3= 0.0 nm
d2= 255.4 nm
d1= 993.8 nm
fitness = 0.029453

SiO2_(therm) n3= 1.457
GaAs_(111) n2= 3.848
AlGaAs70 n1= 3.337
GaAs_(111) n0= 3.848

b)

d3= 79.3 nm
d2= 268.6 nm
d1= 953.4 nm
fitness = 0.080082

SiO2_(therm) n3= 1.457
GaAs_(111) n2= 3.848
AlGaAs70 n1= 3.337
GaAs_(111) n0= 3.848

c)

d4= 1043.6 nm
d3= 275.5 nm
d2= 255.2 nm
d1= 1022.0 nm
fitness = 0.249882

PMMA_950 n4= 1.489
SiO2_(therm) n3= 1.457
GaAs_(111) n2= 3.848
AlGaAs70 n1= 3.337
GaAs_(111) n0= 3.848

Figure 4. a) *Reflectivity spectrum of the GaAs/Al*$_{0.7}$*Ga*$_{0.3}$*As/GaAs sample, with model fit showing the semiconductor thicknesses (255 and 994 nm). The fit shows that there is no SiO*$_2$ *layer on top.* **b)** *Reflectivity spectrum of a GaAs/Al*$_{0.7}$*Ga*$_{0.3}$*As/GaAs sample coated with SiO*$_2$*, with model fit showing the semiconductor thicknesses (269 and 953 nm) and the SiO*$_2$ *layer thickness (79 nm).* **c)** *Reflectivity spectrum of a GaAs/Al*$_{0.7}$*Ga*$_{0.3}$*As/GaAs sample, coated with SiO*$_2$ *and PMMA, with model fit showing the semiconductor thicknesses (255 and 1022 nm) and the thicknesses of the SiO*$_2$ *(276 nm) and PMMA (1044 nm) layers.*

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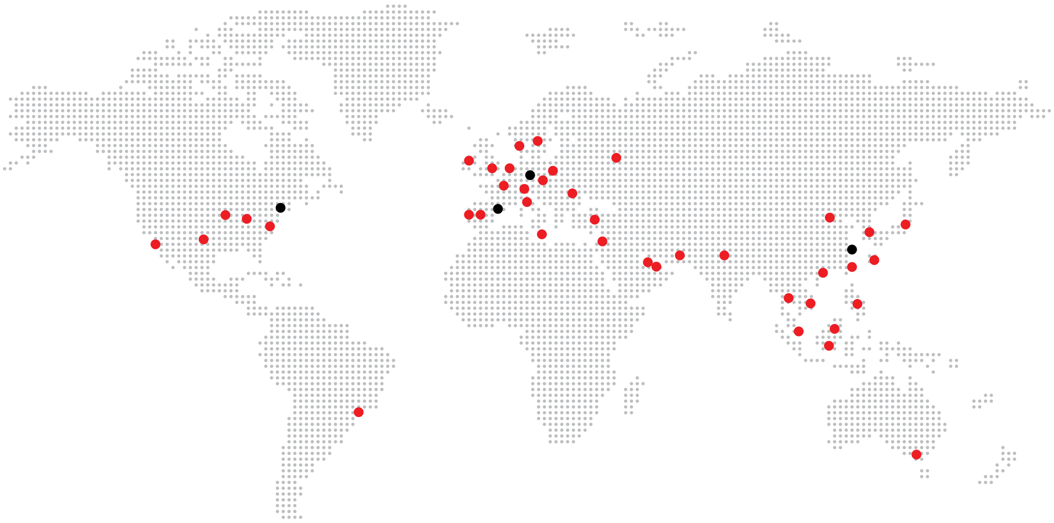

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HEADQUARTERS
SENSOFAR METROLOGY | BARCELONA (Spain) | T. +34 93 700 14 92 | info@sensofar.com

SALES OFFICES
SENSOFAR ASIA | SHANGHAI (China) | T. +86 021 51602735 | info.asia@sensofar.com
SENSOFAR GERMANY | MUNICH (Germany) | T. +49 151 14304168 | info.germany@sensofar.com
SENSOFAR USA | NEWINGTON (USA) | T. +1 617 678 4185 | info.usa@sensofar.com

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