ZnS antireflection coating for Silicon for MIR - LWIR applications

Christian De Vita[1], Marco Asa[2], Mikel Azpeitia Urquia[3], Maria Eloisa Castagna[4], Claudio Somaschini[2],
Francesco Morichetti[1], Andrea Melloni[1]
[1]*Department of Electronics, Information and Bioengineering (DEIB), Politecnico di Milano, 20133 Milano, Italy*
[2]*Polifab, Politecnico di Milano, Via Colombo 81, 20133 Milano, Italy*
[3]*STMicroelectronics, via Olivetti 2, Agrate Brianza,20864 Italy*
[4]*STMicroelectronics, Stradale Primosole, 50-95121 Catania, Italy*
christian.devita@polimi.it

***Abstract*— An antireflection coating (ARC) for silicon devices operating at 10 µm has been designed, fabricated and validated. The ARC is based on ZnS and Al_2O_3 and is deposited at room temperature. Both single and double side ARCs are considered, demonstrating a transmission enhancement respectively of 66% and 89% with respect to an uncoated silicon device.**

***Keywords*— Silicon, antireflection, infrared**

I. INTRODUCTION

Mid-wavelength infrared (3-8 µm) and Long Wavelength InfraRed (8-14 µm) are well-known for being related to the spectrum of environmental gasses [1] and Blackbody radiation at 300 K, whose peak is around 10 µm. These wavelength ranges are of strategic interest for various civilian and military purposes, such as sensing, tracking and imaging.

Silicon, which is the fundamental semiconductor in microelectronics, has nowadays gained a wide role also in photonics, where has been widely exploited in bulk and integrated devices suitable for a plethora of applications. Yet, due to its high refractive index (n_{Si}=3.418@10 µm), strong reflections could occur when interfaced with low index materials, up to 30% for the silicon-air interface, making necessary the use of an antireflection coating. The choice of coating material is crucial in order to guarantee satisfactory antireflection characteristics, suitable manufacturability and low cost. Among the few available materials transparent in LWIR, ZnS has a broad range of transparency, is largely available, is nontoxic, non-hygroscopic and can be deposited both with sputtering and evaporation.

The aim of this work is to demonstrate a ZnS based antireflection coating deposited on silicon plates at room temperature, thus ensuring the CMOS-compatibility of the process.

II. FILM DEPOSITION AND CHARACTERIZATION

The ARC study has been conducted by using 8” Si<100> wafers on top of which the deposition of ZnS films was performed by e-beam evaporation. Targeting a low temperature process, the effect of the deposition temperature on the film quality in term of optical properties, adesion, film stress, etc. was investigated. Stress measurements were performed by KLA Tencor P-17 profilometer able to compute it from the measured wafer curvature by using a Stoney model [2]. Figure 1 shows the stress measured on 1-µm-thick ZnS films deposited from room temperature up to 250 °C. Results show that decreasing the deposition temperature the compressive stress increases by almost a factor three, from -130 MPa to about -350 MPa. Above 200°(compressive stress module < 250 MPa) the adhesion is excellent while with deposition at room temperature the ZnS film exhibits a very poor adhesion, resulting in damaged films with scotch tape test, confirming the behaviour observed in previous works [3][4].

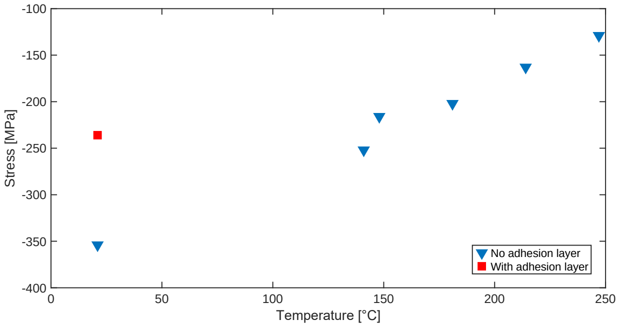


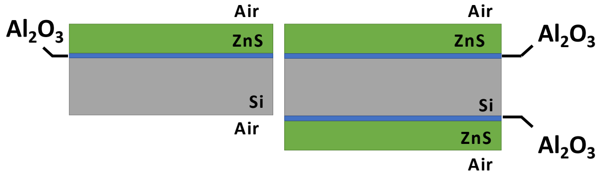
Figure 1. Stress of e-beam evaporated ZnS films deposited on a Si substrate at increasing temperatures. The red square mark indicates the result achieved with a 20-nm-thick intermediate Al_2O_3 adhesion layer.

To improve the adhesion at low deposition temperature a thin interlayer at the ZnS-Si interface has been added. This strategy was successfully adopted in [5], that introduced a MgO film between ZnS and germanium (Ge <111>) substrate. In our process we employed a thin layer of Al_2O_3, whose thickness (20 nm) was optimized in order to provide the best trade-off between good adhesion and have acceptable loss in the LWIR range. The Al_2O_3 layer was evaporated at room temperature prior to ZnS. Thanks to the adhesion layer the stress reduces from -350 MPa to less than -240 MPa (red square in Fig. 1), facilitating the good adhesion of the ZnS film over the entire 8” wafer surface.

III. ANTIREFLECTION COATING DESIGN

The ZnS film was employed to design a quarter wavelength ARC on Silicon, operating in the high MIR and LWIR ranges. Ideally, the refractive index of the matching layer should be equal to $\sqrt{n_{air} n_{Si}}$=1.85. This ideal quarter wavelength ARC could reach up to 94.8% transmission if deposited on both sides of the silicon plate, keeping the reflectance below 1% over a wavelength range of 1.45 µm. However, a suitable material with such refractive index is not readily available in the LWIR and ZnS has been used as a best compromise between technological issues and optical properties. With a refractive index at 10 µm equal to n_{ZnS}=2.2, it ensures a satisfactory transmission up to 90%. Two different ARC structures have been considered, consisting respectively of a single ZnS film deposited on one side of the Si plate and a double side ARC, where two identical ARCs are realized on the two Si surfaces. Targeting a quarter wavelength ARC centred at λ_0 = 10 µm, the nominal thickness of the ZnS is $d_{ZnS} = \lambda_0 / 4n_{ZnS}$= 1.136 µm. For the simulation of the ARC performances the transmission matrix method (TMM) [6] is used. In the simulations the optical field impinging on the structure is assumed to be a plane wave normal to the surface. Results are reported in the 6–14 µm wavelength range, where reliable data on the Al_2O_3 extinction coefficient are available in the literature [7]. Figure 2 shows the comparison between the wavelength dependent intensity transmission (T) and reflection (R) of the single ($ZnS/Al_2O_3/Si$) and double ($ZnS/Al_2O_3/Si/Al_2O_3/ZnS$) ARC with respect to an uncoated Si wafer (dark curves). Results have been smoothed with a 0.15 µm filtering to remove the spurious Fabry-Perot that induces strong oscillations in the spectral behavior.

At the nominal central wavelength the single ARC increases the maximum intensity transmission from 50% to 64% (T-ARC, green line), that is about 28% relative increase. The double ARC structure, instead, improves the transmission from 50% to 83%, that is a relative increase of 66% with respect to the uncoated Si wafer. It should be noted that the mismatch between the transmittance of the ideal quarter wavelength ARC and the double ARC is only around 10%, and our double ARC is able to reduce the reflectivity below 5% over a very broad wavelength range.



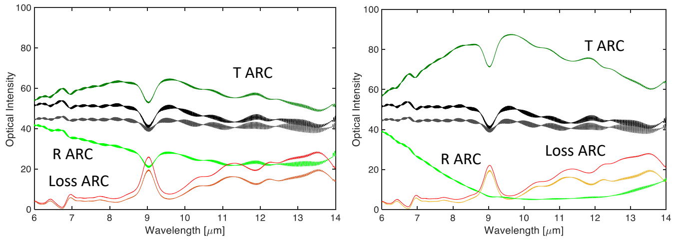


Figure 2. Simulation of the Transmittance (T), in dark green, Reflectance (R), in light green, and Loss, in red, for single and double ARC stacks compared with the bare 700 µm thick Silicon plate (black).

IV. EXPERIMENTAL VALIDATION

The transmittance characterization of the final stack was performed with a Frontier FTIR working in the NIR-LWIR. In figure 3 we provide the results of transmittances related to a plate with and without Al_2O_3: for the wafer with the stack Al_2O_3/ZnS lower losses (lower than 2%/µm) can be observed in the same range, confirming the simulated data, as the introduction of Al_2O_3 almost didn't affect the performances of the ARC. Figure 4 shows the comparison between the measured transmittance of the single ARC (red) and double ARC (yellow) with respect to the uncoated Si wafer (blue line). The transmittance peak at 10 µm for the double coated wafer is 89% and 66 % for the single coated one, in perfect agreement with the expected results.

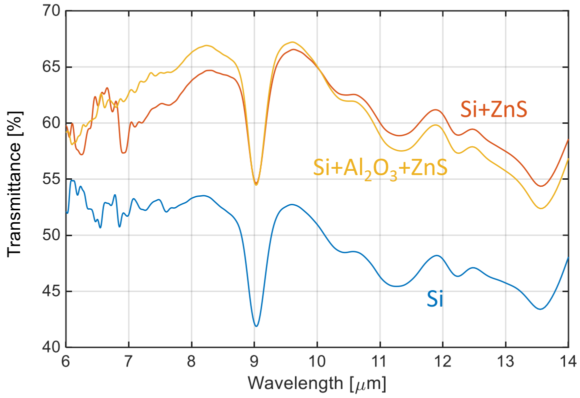


Figure 3. Measured transmittance of the stack with and without Alumina adhesion layer, compared with Silicon

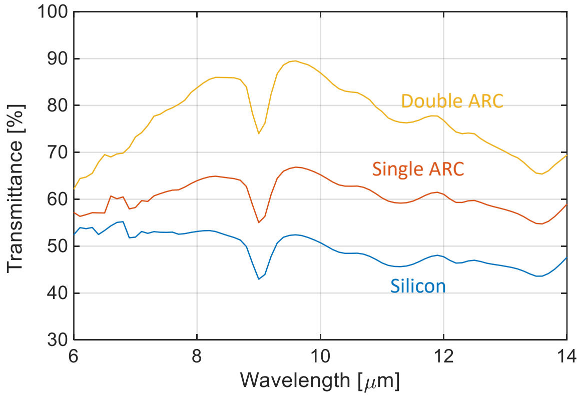


Figure 4. Measured transmittance of single and double ARC w.r.t Silicon

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