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Transmission measurements of multilayer interference filters developed for a full integration on Complementary Metal Oxide Semiconductor chips

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ABSTRACT

We present in this paper a method to measure the transmission spectra of optical filters composed of Complementary Metal-Oxide-Semiconductor (CMOS) compatible materials thin layers in order to be fully integrated on various types of CMOS image sensors (ambient light sensors, proximity detection, red green blue colour imaging, etc.). As the filters have to be deposited on top of a CMOS device, a good approach in order to evaluate with accuracy their response on chip is (i) to achieve the stacks on Si wafers (as it is the case for the CMOS sensor) (ii) then to perform a direct bonding of the structure on glass wafers (iii) in the end to remove the entire bulk silicon. In this way, we show the measured spectral responses of multilayer interference filters and can check particularly the agreement of the transmission peak with the theoretical calculations and its reproducibility wafer to wafer. It enables to optimize the filters optical designs and to demonstrate that the developed filters fulfill typical CMOS requirements of integration and reliability.

1. Introduction

Complementary Metal-Oxide-Semiconductor (CMOS) based image sensors have been widely investigated these past years because they offer the opportunity to improve the miniaturisation and reduce the power consumption and the component and packaging costs of imaging systems [1,2]. Due to their sensitivity in the visible and near infrared (NIR) ranges, CMOS image sensors can be used for different applications than traditional red green blue colour imaging [3]. Particularly, the ambient light sensing (ALS) and the adjustment of the display's brightness and contrast may be provided by the green signal while the presence detection is typically carried out via a small band-pass channel in the NIR. Therefore, the use of optical filters with adjusted and optimized responses is required in more and more fields of applications and there is a very high interest in developing fully integrated filters on chip which consists of a stack of CMOS-compatible thin layers.

The integration of multilayers filters on chip has already been shown in previous studies [4,5,6,7,8]. The spectral signatures of filters were clearly observed in quantum efficiency measurements and compared to theoretical predictions. However, measured responses on CMOS and simulated curves do not usually show a perfect agreement with the presence of slight mismatches in magnitude and shifts in wavelength. It is very complex to differentiate the errors resulting from the filter stack and the CMOS stack. Moreover it is difficult of characterizing with precision the absorption coefficient of materials which can be measured only in reflection. The possibility to carry out transmissions measurements becomes thus essential with a view to optimize the filters designs and improve their characteristics and performances. It enables to accurately check the respect of the filter responses to specific performance criteria before the integration on chip and to estimate the agreement between the measured and simulated measurements particularly for the wavelength, intensity and full-width at half-maximum (FWHM) of transmission peaks. The most direct approach to measure the transmission spectra for a multilayers optical filter would be to deposit the stacks on a transparent material like the glass. The use of glass wafers is usually compatible with standard microelectronics processes [9,10] and commercial substrates of 200 mm and 300 mm are easily available. But the processing of glass substrates is generally impossible with typical reactors and tools used in the semiconductor industry because the automatic detection and handling of the glass wafers by the robots cannot be performed correctly. Moreover the deposition rates and morphological properties of many materials change according to the nature, thickness or even surface orientation of substrates. Consequently, the optimization of filter designs by the transmission measurements of stacks deposited on glass substrates is not relevant and the optical characterizations of multilayers have to be performed on filters deposited on

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silicon substrates in order to be applied for the integration on CMOS chip.

In the present paper, we report a method to measure the transmission response of multilayers optical filters deposited on Si wafers. We describe the designs and materials used to perform the studied filters as well as the method to calculate and optimize their optical response. We show the possibility of bonding the filter stacks on a glass substrate and removing the Si bulk with chemical/mechanical thinning down in order to obtain the measured spectral transmittance of multilayers stacks made in similar conditions to the integration on CMOS chips. By comparing the measured and simulated spectral transmittances, we observe an excellent agreement and we demonstrate this technique enables to evaluate with precision the performance of filters in terms of transmission response and reproducibility, what is essential for the filters designs optimization.

2. Filter design description

In this study, we design and make bandpass filters using single or multiple Fabry-Perot (FP) cavities. The basic principle is to alternately deposit materials with different refractive index and commonly used in foundries, to obtain interferential multilayer stacks. In the prospect to integrate ambient light and presence detection on CMOS chip, we investigate here filters with respectively the ALS and NIR functions. The ALS filtering is designed with Cu-dielectrics multilayer stacks. These metal-dielectrics interference filters provide both good transmittance in green (above 50%) and efficient NIR cut-off filtering. The dielectric materials chosen here are both SiN and SiO_2 because (i) they are widespread in the semiconductor industry (ii) transmission in the band-pass and rejection can be enhanced by introducing dielectric layers with different refractive indices in the filter [11] (iii) SiO_2 is a better candidate than SiN to provide a surface adhesion with a glass substrate. For the realization of NIR filters, non-metallic multilayers design is proposed and made by interleaving SiO_2 films with a-Si films because aSi/SiO_2 stacks are well known to provide the IR band-pass functionality [7,12]. Filters were designed with manually adjusted target transmittances and the random optimization tool in Optilayer software [13] to determine appropriate layer orderings. The spectral responses are calculated with the optical constants deduced from single layer ellipsometric measurements on Si for all the materials except the copper (Cu). In the case of metallic materials, the characterization of single layers by ellipsometry led to large uncertainties. So we designed filters with already available data (Palik data and optical indices calculated by a multi-filters characterization method [14] for a copper studied a few years ago and deposited in another physical vapor deposition (PVD) tool) and provide two different calculated spectral responses for the Cu/dielectrics filters.

Fig. 1 shows a schematic drawing of the proposed filters with (a) the NIR multilayer a-Si/SiO_2 stack and (b) the ALS multilayer Cu-dielectrics stack. The design of a-Si/SiO_2 filters includes 9 layers and consists of a narrow band-pass filter centred in the NIR with high rejection. There are residual bumps that can further be reduced by adding a black resist over the filter, or by a design with more layers. For the metal/dielectric filter, a simple cavity Cu/dielectric stack including two metallic layers and one SiN spacer was found to be the best trade-off between the technological considerations and the agreement of the spectral response with the ALS requirements. The optical design was also constrained by a few technological considerations. The dry etching feasibility of stacks related to the limited thickness of the photoresist was taken into account to limit the maximum thickness of filters around 1.4 μm. The minimum thicknesses of Cu and other monolayers (a-Si, SiO_2, SiN) were respectively set to 20 nm and 50 nm to avoid any additional deposition process developments in term of deposition rate decrease and control of thicknesses uniformity. And only Cu/SiN interfaces were considered in the design because SiO_2 oxidizes Cu and induces delamination of metallic film.

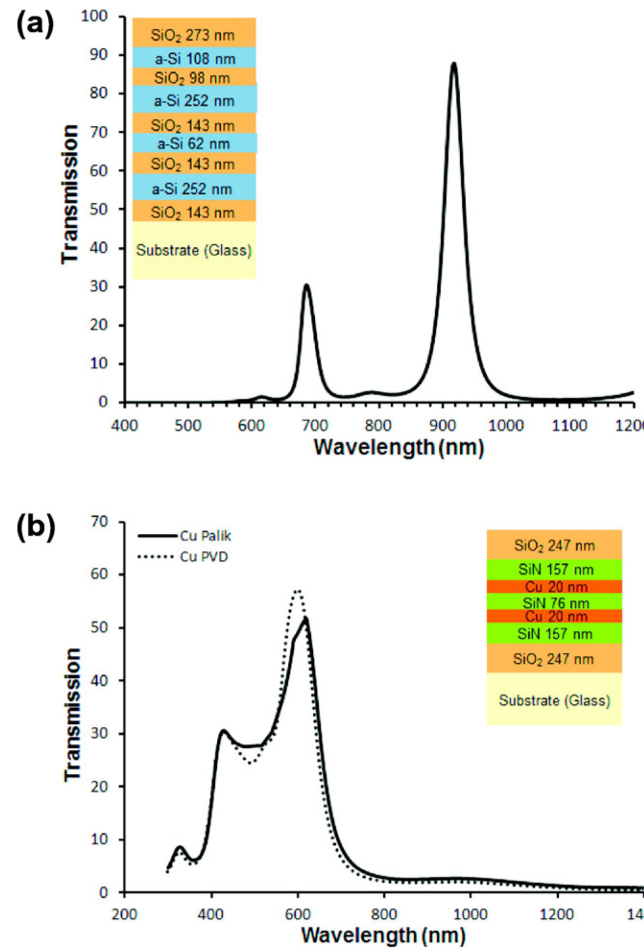

Fig. 1. Design of normal calculated transmission spectral responses on glass substrate of a) NIR multilayer Si/SiO2 FP filter and b) ALS multilayer Cu/SiN/SiO2 FP filter.

3. Experimental details

3.1. Filter layer deposition

All the experiments were carried out on *p*-type 200 mm Si (100) wafers covered by a 143 nm and a 247 nm thick thermal SiO_2 layer for respectively the a-Si/SiO_2 and the Cu/dielectrics filters. The SiO_2 and a-Si films were deposited by plasma enhanced chemical vapor Deposition (PECVD) and the Cu and SiN layers by PVD respectively in single-wafer CENTURA and ENDURA systems of Applied Materials. The thicknesses of all deposited layers have been calibrated on single layers using an ALERIS 8500 KLA-TENCOR ellipsometer or a BRUKER D8 FABLINE X-ray-reflectometer. Scanning electron microscopy (SEM) images have been acquired on a Hitachi 5500 tool with an operating voltage ranging from 1 kV to 30 kV.

The Cu thin films were deposited at ambient temperature using Direct Current (DC) magnetron sputtering in constant power mode. The working pressure was set between 0.15 and 1.5 Pa with a constant Ar flow rate of several tens of sccm. In order to achieve a high control on the layer thickness and uniformity, we decreased the power of the plasma down to about 500 W which enabled to obtain a deposition rate as low as 1.5 nm/s. The SiN films were performed by pulsed DC magnetron sputtering with a power of plasma kept constant around 1 kW and a low-frequency generator (50–100 kHz). The maximum sample temperature during the deposition was estimated to be 150 °C at a pressure of 0.15 Pa and an Ar/N_2 gas flow ratio set at a value between 1 and 2. The deposition rate obtained is close to 0.5 nm/s. All the layers of the Cu/SiN stacks are successively carried out in two different chambers of the