Sputtered Ge-Si heteroepitaxial thin films for photodetection in third window

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ABSTRACT
DC-Pulsed Magnetron Sputtering (PMS) allows to produce heteroepitaxial p-type Germanium thin films on 6" Silicon wafers. Integrated p-n photodiodes, based on DC-PMS deposited Ge/Si heterojunctions, feature flat responsivity over the whole third communication window.

1. INTRODUCTION
Ge-on-Si photodiodes are a solution to monolithically integrate signal detection at third telecommunication window, aiming at C-MOS compatible photonics [1]-[7]. High bit-rate applications typically require the growth of epitaxial Ge films either by CVD ( UHV-CVD, RP-CVD, LE-PECVD) or by MBE [2]-[7] and specific solutions to the Ge-Si lattice mismatch that ultimately affects performances [2],[3]. However, when targeting signal bandwidths up to a few GHz and for the purpose of integrated optical power monitoring, less critical technological approaches can be pursued and poly-crystalline p-type Ge can be adopted [8]. In particular, sputtering is effective to grow Ge films ranging from amorphous to epitaxial; the possibility to obtain hetero-epitaxy on Si substrates has also been reported [9]-[11].

In this work we demonstrate DC-Pulsed Magnetron Sputtering (DC-PMS) as a sustainable technology for the production of hetero-epitaxial p-type Germanium thin films on 6" wafers, to make integrated p-n photodiodes for Silicon photonics.

2. EXPERIMENTAL
Germanium films have been grown in a 1-m³ volume sputtering system (VS80 by KenoSistec, Italy). A crystalline Ge target (99.999% purity) was bonded onto a rectangular (12” x 2”) magnetron cathode in vertical configuration. The growth chamber was evacuated to a base pressure of 8x10⁻⁹ Pa by turbo pumping; ultrapure Ar (99.9999%) plasma was activated by a DC-pulsed generator (pulse rate =350 kHz). The 6” Si (100) wafer substrates, pre-cleaned in BOE solution to remove native oxide and then rinsed in de-ionized water, were mechanically clamped onto a chuck and positioned at 10 cm from the target. The chuck oscillated in front of the Ge target to improve deposited film thickness uniformity over the whole 6” wafer surface. After purging the chamber down to the base pressure, the 6” Si wafer underwent 1-hour heating at 425 K to desorb water and clean the surface. Before starting the growth process, the surface of the Ge target was also cleaned by presputtering for 5 min. Films 100-200nm thick have been deposited. Process parameters are summarized in Table I.

| Table I: Sputtering and RTP processing parameters for amorphous and epitaxial Ge films |
|----------------------------------------|----------------|----------------|----------------|
| Power (W)                             | 800            | 800            | 550            | 800            |
| Voltage (V)                           | 340            | 340            | 298            | 340            |
| Target Current (A)                    | 2.35           | 2.35           | 1.84           | 2.35           |
| Ar Flow (scm)                         | 200            | 200            | 250            | 200            |
| Process Pressure (Pa)                 | 1.9 E-4        | 1.9 E-4        | 2.2 E-4        | 1.9 E-4        |
| Deposition Rate (nm min⁻¹)            | 17             | 17             | 13             | 17             |
| Growth T (K)                          | 503            | 643            | 643            | 643            |
| RTP (ramp rate, T_max, process)       | no             | no             | no             | 50 Ks⁻¹, 673 K, 30 s |

As proved by XRD, amorphous films were obtained at growth temperatures T < 553 K; by performing a post-growth classical annealing of amorphous films at 773 K, randomly oriented polycrystalline structures were generated; films grown at T > 573 K can be considered to be epitaxial, as confirmed by TEM diffraction analysis.
reported in Fig. 1(a). HREM shows a polycrystalline co-oriented columnar structure, with a preferred (100) orientation, with domain average size of 50 nm and surface roughness of about 10 nm; the Ge/Si interface is not atomically sharp (about 1 nm roughness); no residual SiO₂ was detected, as confirmed also by RBS measurements; planar defects (stacking faults and twin lamellae) and dislocations are visible at the Si/Ge interface and extended in depth in the film. By decreasing the growth rate and/or by adding a post-deposition RTP stage, the epitaxial quality of the Ge layer was improved and surface roughness below 1 nm has been obtained. This result was confirmed by AFM topography on Ge films sputtered at T = 643 K: in case of as-deposited films, a typical example of surface roughness was characterized by peak-to-peak Z range = 6.86 nm and root-mean-square Rq = 0.492 nm; after RTP treatment values have respectively changed to Z range= 0.725 nm and Rq = 0.0862 nm.

![TEM analysis of the Si/Ge film](image)

Fig.1: TEM analysis of the Si/Ge film, grown at T = 643 K. (a): Electron diffraction pattern: Ge is grown epitaxially to Si displaying the same diffraction pattern as Si. The internal (and weaker) reflections come from the Ge layer; (b): HREM picture of the interface region; (c) cross-section of Ge-on-Si film after RTP stage: surface roughness amplitude below 1 nm is obtained and the penetration of threading dislocations is also reduced.

Linear optical properties of Ge films were evaluated by spectroscopic ellipsometry. A distinguishing feature of films sputtered at T= 643 K and RTP-annealed, when compared to other epitaxial growth techniques [4], is the absence of strong decrease in absorption on the spectral range 1500 nm ÷ 1600 nm; values such as n|@ 1500nm= 4.2035, α|@ 1500nm = 5308 cm⁻¹, n|@ 1560nm= 4.1941 and α|@ 1560nm = 4823 cm⁻¹ are obtained. Uniformity in refractive index and film thickness onto the whole 6” wafer surface was ellipsometrically characterized by taking 49 samples equally distributed in angle and radial distance from the wafer center. Measured standard deviations are respectively as low as σn = 0.2% and σt = 1% of the average values.

A combined compositional analysis (XPS, SIMS and RBS) excluded significant contamination during the deposition process of the sputtered film. Even in the absence of intentional doping, polycrystallinity in Ge is expected to involve p-type conductivity as a consequence of native intrinsic defects [10]-[15]. Resistivity, carrier concentration and mobility have been assessed by Hall measurements for the sputtered films. Reproducible results have been obtained on polycrystalline layers, with good uniformity at the wafer scale. For films of good morphology, as resulting from the sputtering process recipe and prior to RTP post-processing, hole density in the range 8 x 10¹⁵ cm⁻³ < p < 2 x 10¹⁶ cm⁻³ and mobility as μₜ = 1510 cm²/(V sec) have been measured. Measured values for the carrier concentration and the mobility were respectively lower and higher than those usually reported for the poly-Ge case [12]-[14] and approach typical values of epi-Ge films [9],[11]-[13],[15]. These results essentially agree with the quasi-epitaxial nature of our as-deposited films, with no strong contamination, as shown by TEM analysis. A suitably tuned RTP post-growth stage can be a further tool to optimize the transport properties of the films according to designed performances.

Heterojunction p-n Ge/Si test mesas photodiodes have been made, by patterning 120 nm thick Ge films sputtered onto n-type Si wafers (ρ = 5÷10 Ωcm) and by evaporating Ti-Au contacts. Photodiodes were backside-illuminated. The curve in Fig. 2(a) is an example of measured responsivity vs. applied voltage at λ = 1.5 μm. Fig. 2(b) highlights the spectral flatness in responsivity on C-band and L-band. This behavior, which agrees with measured flatness in absorption spectrum and distinguishes these sputtered-based photodiodes from other realizations as reported in the literature [3], is particularly promising for applications to multi-wavelength photonics.
Fig. 2: (a) Test photodiode responsivity @ $\lambda = 1.5$ μm; (b): Example of responsivity spectrum in the third window.

3. CONCLUSIONS

A process to heteroepitaxy of $p$-type Ge thin films on 6” Si (100) wafers by DC-pulsed magnetron sputtering and post-growth RTP has been described. Uniformity of performances at the wafer scale and flat responsivity spectrum around $\lambda = 1.55$ μm featured by test $p-n$ Ge/Si photodiodes suggest that DC-PMS can be a promising C-MOS compatible technology to integrated photodetection in third communication window.

REFERENCES


