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# Characterization of zinc sulfide waveguides for nonlinear photonics

A. Lemoine<sup>1</sup>, A. Letoublon<sup>1</sup>, A. Naim<sup>1</sup>, T. Batte<sup>1</sup>, C. Cornet<sup>1</sup>, Yannick Dumeige<sup>1</sup>, Christophe Levallois<sup>1</sup>, Yoan Léger<sup>1</sup>

<sup>1</sup>Univ Rennes, INSA Rennes, CNRS, Institut FOTON - UMR 6082, F-35000 Rennes, France  
Author e-mail address: antoine.lemoine@insa-rennes.fr

**Abstract:** This paper presents the advantages of zinc sulfide (ZnS) for second order nonlinear photonics through structural and optical characterizations of ZnS thin films and waveguides.

## 1. Introduction

The nonlinear optical phenomenon resulting from matter-radiation interaction has been considerably improved thank to the development of photonic devices allowing strong confinement of the electromagnetic field within a guiding structure based on a nonlinear optical material. [1]. Up to now, only few studies have been focused on zinc sulfide (ZnS). This material is promising for non-linear optics since it has as a high refractive index at telecom wavelengths [2], a wide spectral band of transparency, high second [3] and third order non-linear coefficients [4] and a polycrystalline structure that can potentially be put to good use for non-linear process [5]. The variety of ZnS deposition methods, some of them low-cost, also represents an interesting technological advantage from an application point of view. In this work, we describe the structural and optical properties of ZnS thin films deposited by magnetron sputtering, as well as the fabrication process of the first ZnS based waveguides and their linear characterization.

## 2. Characterization of sputter deposited ZnS thin films.

In this study, zinc sulfide (ZnS) thin films were deposited by magnetron sputtering. To ensure an optimal deposition environment and a high quality ZnS layers, a clean vacuum system (residual pressure in the  $10^{-7}$  mbar range) and stable plasma conditions have been used. A pre-deposition step was performed where the RF plasma power is progressively increased until 85 W in 5 minutes, then a 500 nm thick ZnS layer was deposited onto a Si substrate over a 30-minute period. For such low plasma power, the heating on the substrate is strongly limited and ZnS can be considered as deposited very close to the room-temperature. Atomic force microscopy (AFM) analysis of the ZnS thin-film surface revealed a root mean square (RMS) roughness of 1 nm, which is suitable for the fabrication of photonic structures. The dispersion curves ( $n$ ,  $\alpha$ ) obtained via ellipsometry are presented in Figure 1(a) and the bandgap energy of 3.47 eV have been deduced from the  $\alpha$  curve (see the inset). This value is slightly lower than that of pure zinc blende ZnS (5.4 eV) but such measured optical properties demonstrate a wide range of transparency for our ZnS layers (at least from 450 nm to 2000 nm).

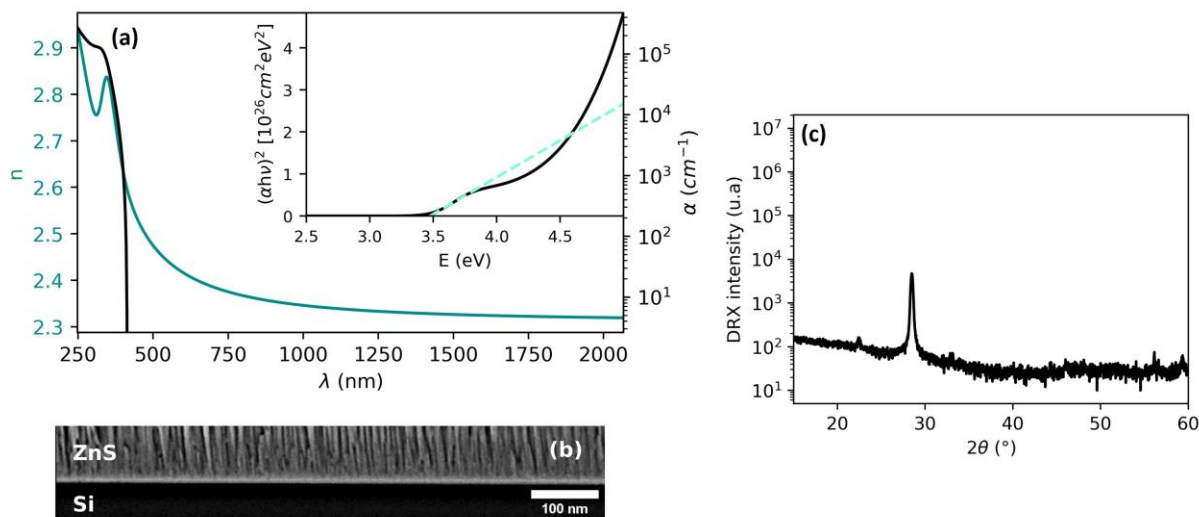


Fig. 1 a. Ellipsometric dispersion curve of the refractive index ( $n$ ) and absorption coefficient ( $\alpha$ ) of a ZnS thin film. Insert shows Tauc plot used for obtained the bandgap energy b. SEM image of a ZnS thin film deposited on germanium. c. X-ray diffraction pattern of a ZnS thin film deposited on SiO<sub>2</sub>/Si.

Additionally, under the experimental deposition conditions, the ZnS thin film exhibited a columnar structure, as evidenced by scanning electron microscopy (SEM) images of the thin film cross-section (Figure 1b), suggesting a polycrystalline nature. Comparing the X-ray diffraction pattern (Figure 1c) with theoretical patterns from databases such as the Crystallography Open Database, we identified only the 111-diffraction peak which suggests that crystallites are mainly oriented with (111) plans coplanar to the surface. Further structural analysis is required to evaluate the crystal rotation around this axis from one column to the next.

### 3. Fabrication and linear characterization of ZnS waveguides

The fabrication of the ZnS waveguides is realized through a four-step process. Initially, a silicon substrate undergoes thermal oxidation to produce a 1  $\mu\text{m}$  thin film of  $\text{SiO}_2$ , which serves as the cladding layer for the ZnS waveguides. Following this, a 500 nm thick layer of ZnS is deposited with the same conditions than the one previously described. The third step involves an electron-beam lithography process combined with a dry etching process by RIE (reactive ion etching) to form a waveguide. The gas mixture for an efficient etching of ZnS films is based on  $\text{CH}_4$ ,  $\text{H}_2$ , and Ar (Figure 2.a).

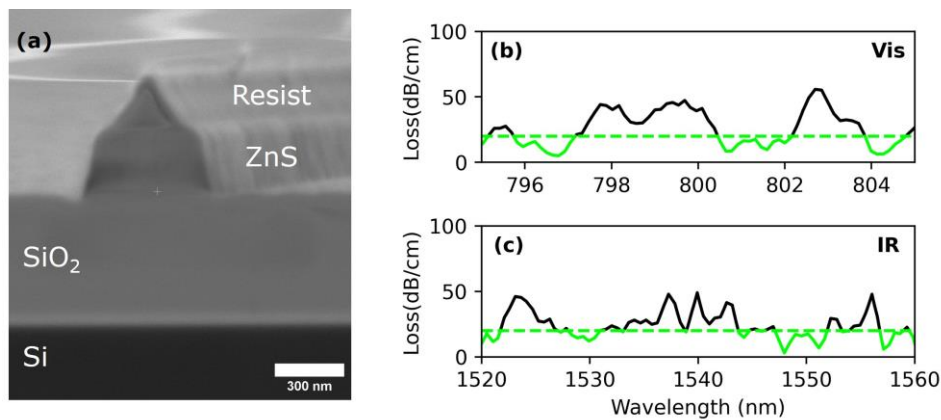


Figure 2 a. SEM image of a clived ZnS waveguide. b,c Propagation losses in visible and infrared region. Values in green are less than 20 dB/cm.

We used Fabry-Perot (FP) fringe measurements [6] to assess the propagation losses in the ZnS guides at telecom and visible wavelengths (Figure 2 b,c). Their contrast is directly related to the optical losses in the cavity made by the waveguide and its cleaved facets, allowing us to estimate propagation losses lower than 50 dB/cm in the whole wavelength range and even in the order of 10dB/cm in some spectral regions. These values are competitive with other more mature platforms, even with sub-wavelength dimensions, and are compatible with second harmonic generation, which was lately observed and is now under characterization.

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