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Short communication

Low-loss magnesium films for plasmonics

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ABSTRACT

The optical properties of pure nanostructured magnesium films deposited on glass, Si and GaAs substrates using DC magnetron sputtering are examined in this work to determine the potential of Mg as plasmonic material in the ultraviolet (UV) to near-infrared (NIR) spectral range. Using film thicknesses ranging from 210 to 910 nm, the corresponding optical constants over the wavelength range of 250–1700 nm were measured using a variable angle spectroscopic ellipsometer and these results are compared to reference Al thin films. The optical constants of Mg depend on the film thickness. From the perspective of plasmonics applications, we find that the best values are observed in this work for the 910 nm thick Mg film on glass substrates. The film morphology and structure of the Mg films were characterized using atomic force microscopy, scanning electron microscopy, stylus profilometry and X-ray diffraction. The optical dielectric constants and plasmonic figures of merit are strongly influenced by the film structure. The results show that smooth and [0 0 0 2] textured magnesium films have extremely low loss, superior or comparable to aluminum films in portions of the UV spectrum.

1. Introduction

The field of plasmonics has grown tremendously over the last decade, largely because of the broad range of potential applications. At the interface between a metal and dielectric, bound electromagnetic waves that are coupled to a collective oscillation of electrons are referred to as surface plasmon-polaritons (SPPs) [1]. The terminology arises from the fact that within the metal, the penetration depth of the electromagnetic waves is typically only a few tens of nm at optical frequencies. A unique attribute of SPPs is their dispersion properties, which can allow for orders of magnitude enhancement in the local electromagnetic field in sub-wavelength metallic structures. In order to optimally utilize this behavior, a figure of merit for the plasmonic response can be defined and this figure of merit depends upon the dielectric properties of the metal and the structure geometry. The latter parameter is important, since there are two extreme cases: localized plasmon resonances (LSPR) in nanoparticle geometries and propagating SPPs in planar geometries.

The dielectric properties of a material are associated with the electric polarization induced in a material by incident radiation and can be described by the complex permittivity, or dielectric function, denoted by $\varepsilon = \varepsilon_1 + i\varepsilon_2$ [2–4]. For SPPs to exist, the real part of the dielectric constant (ε_1) of the metal must be negative while that of the adjacent dielectric material must be positive. This condition is satisfied in the IR-visible wavelength regions for most dielectric/metal interfaces. In plasmonics applications that target the visible region of the spectrum, metals such as Au, Ag and Al tend to be the dominant materials of interest. This arises from the fact that they exhibit plasma frequencies in the UV, with comparatively low loss in the visible. These losses typically result from (i) the interaction of free electrons with other electrons, phonons, lattice defects such as solutes and dislocations, and grain boundaries and (ii) interband transitions associated with bound or inner shell electrons. Thus, low loss metals with very high electron densities (high plasma frequencies), an absence of interband transitions in the spectral regions of interest, and structures with minimal defects are of great interest for general plasmonic applications [5–8].

The use of plasmonics in the UV spectral range has often been overlooked, but is of interest as many important chemical/biochemical reaction steps are associated with these energies. UV plasmonic structures are therefore very attractive for use in enhanced chemical synthesis and other photochemical processes, UV spectroscopy for sensing and detection, and energy harvesting applications [5]. Al is often considered the best plasmonic metal across the UV range due to its high plasma frequency and absence of interband transitions in this region. However, it suffers from drawbacks including a large electron damping factor and the formation of a very stable oxide layer that is of concern in both fabrication and use. In this context, Al and Mg share two important attributes. First, Mg has no d-shell electrons and therefore no interband transitions involving d-shell electrons can occur.

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Thus, Mg is expected to exhibit low losses in the visible-UV range. Second, Mg forms a thin (~20 nm thick) protective native oxide (MgO) film [9], which is less stable than aluminum oxide. This needs to be considered in the design and fabrication of plasmonic devices. Prior experimental measurements of optical constants in magnesium thin films and single crystals in the UV–vis spectral range date back to 1975 and earlier and are summarized by Palik [10–22]. Vidal-Dasilva et al. [23] have more recently measured optical properties in the energy region of 25–1300 eV using transmission measurements. These energies correspond to a wavelength range of 49.5–0.954 nm, and cover portions of the X-ray and extreme UV spectral regions. No recent experimental measurements of optical constants of Mg have been reported and recent papers refer back to data summarized by Palik or present theoretical estimates of plasma frequencies [24–27]. The data of Palik cover the spectral range of 0.02 (50 keV)–17,700 nm (0.07 eV) but with minimal sampling in the 250–1700 nm range. Moreover, the measurement of optical constants is sensitive to the sample structural characteristics. Given that only sketchy descriptions of the samples and their structural details appear in these early reports, there is great need for a detailed re-examination of the optical properties of Mg.

In this paper, we present a detailed examination of the optical properties of nanostructured magnesium films deposited on glass, Si and GaAs substrates using DC magnetron sputtering to determine the potential of Mg as a plasmonic material, especially as compared to Al in the UV region. The optical constants were measured using a variable angle spectroscopic ellipsometer (VASE) as a function of film thickness and substrate material. The film morphologies and structures were characterized using atomic force microscopy (AFM), scanning electron microscopy (SEM), stylus profilometry and X-ray diffraction and were correlated with the optical behavior. We show that higher figures of merit and lower losses than Al can be achieved in certain UV wavelength ranges and that the optical constants observed are highly sensitive to the structural characteristics of the film.

2. Experimental work

We prepared magnesium sputtering targets by rolling and machining a very high purity magnesium (99.99+%) sample obtained from US Magnesium. The machined target had a diameter of 50 mm and thickness of 6.25 mm. The DC magnetron sputtering was carried out in an ultra-high vacuum (UHV) chamber using electronic grade argon sputtering gas. The UHV deposition chamber was a modified surface analysis chamber from MDC Vacuum Corporation and fully dedicated for this work. The chamber was made of stainless steel with Del-Seal® flanges and capable of achieving vacuum levels of 10^{-11} Torr. The chamber was evacuated for 16 h using a turbo pump to a base vacuum level of $<2 \times 10^{-7}$ Torr. Argon gas was then introduced at a flow rate of 2.5×10^{-2} cc/min and maintained for 3 h with the turbo pump on. The sputter gas pressure in the chamber was controlled using a bellow valve between the chamber and turbo pump. The sample to target distance was 70 mm and sputtering was carried out at a pressure of 2.5×10^{-3} Torr using the 50 mm DC/RF magnetron sputtering source and an Advanced Energy 500 W DC sputtering power supply. The target was sputter cleaned for 10 min prior to each deposition to remove the oxide scales on the target surface. Using a sputtering power of 25 W, the deposition rate was ~6 Å/s. We used Fisher brand pre-cleaned glass slides (from Fisher Scientific), and polished (1 1 1) Si and (2 0 0) GaAs wafers, since the Mg films needed to be deposited on optically smooth surfaces. The substrates used were ~25 mm × 25 mm in size and were all cleaned using ultrasonic agitation in ethanol. Magnesium films with nominal thicknesses of 210, 590 and 910 nm were deposited on glass, (2 0 0) GaAs and (1 1 1) Si substrates. A stylus profilometer (KLA Tecor P-20h Long Scan Profiler TENC 302 Model) was used to measure the film

Table 1
The average grain size values obtained for glass, Si and GaAs substrates.

Substrate	Film thickness (nm)	Average grain size (nm)
Glass	210 ± 23	76
	590 ± 30	112
	910 ± 19	205
Silicon	210 ± 11	78
	590 ± 27	102
	910 ± 7	172
GaAs	210 ± 22	82
	590 ± 14	104
	910 ± 19	177

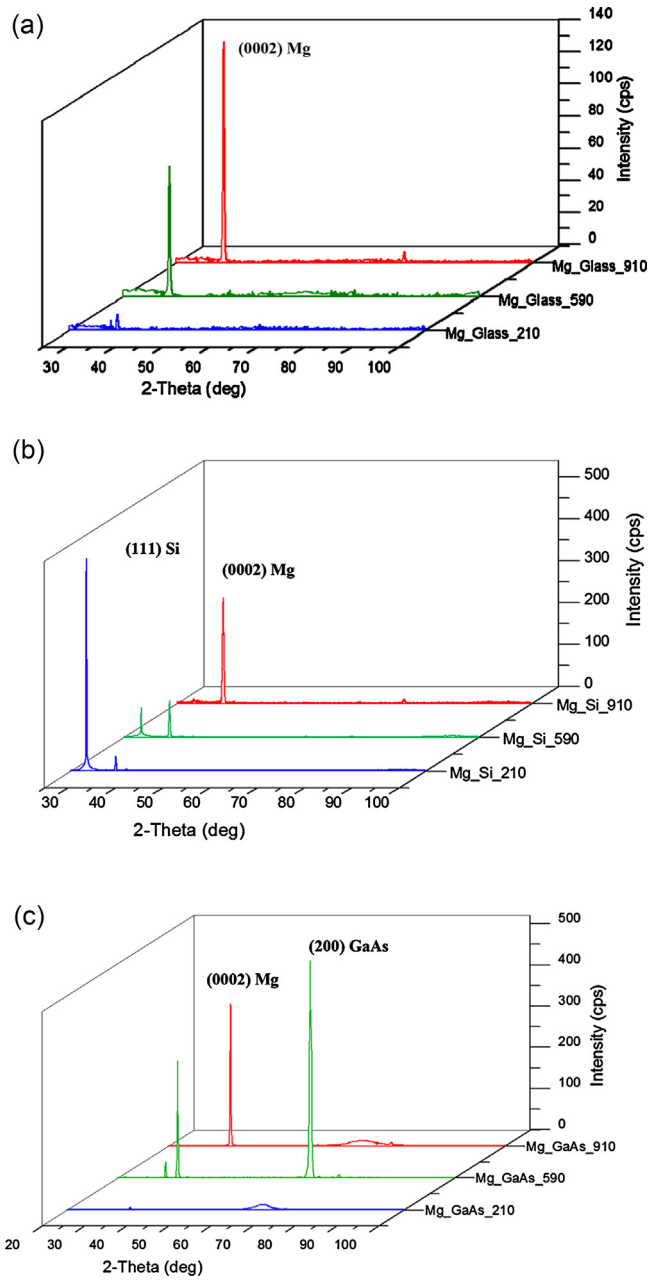

Fig. 1. X-ray diffraction patterns of Mg films deposited on (a) glass, (b) Si and (c) GaAs for nominal Mg film thicknesses of 210 nm, 590 nm and 910 nm.