Available online at www.sciencedirect.com

ScienceDirect

Optical Materials 30 (2007) 328–333

www.elsevier.com/locate/optmat

Optical excitation of surface phonon polaritons in silicon carbide by a hole array fabricated by a focused ion beam

Herman Högström *, Sima Valizadeh, Carl Gustaf Ribbing

Department of Engineering Sciences, The Ångström Laboratory, Uppsala University, Box 534, SE-7851 21 Uppsala, Sweden

Received 16 August 2006; received in revised form 25 October 2006; accepted 10 November 2006
Available online 30 January 2007

Abstract

Silicon carbide (SiC) is a polar material with a lattice resonance in the thermal infrared causing a wavelength interval with a negative dielectric function. Within this interval SiC can support surface waves. To excite surface waves, i.e., surface phonon polaritons (SPP), the sample has to be structured with a periodic micro-pattern. The possibilities of using a focused ion beam (FIB) for microfabrication of periodic microstructures in silicon carbide (SiC) is investigated. We present optimized parameters for the microfabrication of SiC with a FIB, as well as calculated and experimental optical results confirming the sensitive optical properties of the material required for the surface excitation are not destroyed by the preparation process.

Keywords: Ionic crystals; Microstructure fabrication; Surface waves; Polaritons

1. Introduction

With the new possibilities for micro and nanostructuring of materials, e.g. by focused ion beam (FIB) fabrication, there has been an increased interest in making and investigating different photonic structures and their optical behavior. The possible applications for these structures range over many different disciplines: from physics, chemistry to material science and biology.

A new structure, first suggested about 20 years ago, is photonic crystals [1,2], which is an artificial material with a refractive index varying periodically in 1–3 dimensions. The concept was proposed in 1987 [3,4] and has opened up a new field of research. It was demonstrated, theoretically and experimentally, that photonic crystals could have photonic band gaps, i.e., energy intervals with no allowed states for photons, just as a periodic arrangement of atoms may create an energy gap for conduction electrons in a semiconductor. The periodic modulation of the refractive index is analogous to the periodic crystal potential electrons experience in a crystal. By choosing the structure, the lattice constant and two media, a photonic gap can be positioned at a desired wavelength. Transmittance and reflectance of light can thereby be controlled, just as electric conductivity can be controlled in semiconductors. Forbidden gaps for photons with certain energies had been observed earlier for one-dimensional structures [5]. In photonic crystals defects can be introduced and used as resonant cavities or wave-guides. If light is guided into a chain of defects and it has this "dopant" frequency within the energy gap, it is trapped. It cannot radiate into the crystal and it can be guided around corners with much smaller radius than conventional optical components. A resonant cavity can be used for laser applications or studies of atomic transitions where a very small bandwidth and high Q-value is wanted.

Another type of photonic microstructures is surface polaritonic devices in which the electromagnetic signal/excitation is transported as a polarization wave along the surface of the material [6]. If the polarization wave in the material is composed of electrons or phonons they are named surface plasmon polaritons or surface phonon

* Corresponding author.
E-mail address: hogstrom@physics.aau.dk (H. Högström).

0925-3467/$ - see front matter
doi:10.1016/j.optmat.2006.11.064

polaritons (SPP), respectively. Surface polariton, SP, is the term we will use for the surface excitation, regardless the source. The physics of surface polaritons has been known for a long time, but in 1998 when enhanced optical transmission [7] through sub-wavelength holes in a metal film was first observed it increased the interest for this field. Earlier works show that surface excitations can be used for biosensing [8,9], biophotonics [10], data storage [11], microscopy [12] and more recently wave-guiding [13,14]. The combined functionality of photonic band gap structures and plasmonic devices has also been demonstrated [15]. Bozhevolnyi et al. showed that a surface excitation can be guided by a line defect acting as a wave-guide through a periodic lattice of holes in a metal film. The main advantages with polaritonic devices are the sub-wavelength dimensions and the possibilities to interconnect with optical systems and nano-imaging/spectroscopy, which we will discuss later. Most work in the field of surface polaritons has been performed with metals [16], but a few reports have also been published for non-conducting materials [17–19].

In this project we chose to work with SiC because of its optical behavior in the infrared. Since it is a well established and durable material it is possible to work with samples of high quality. However, surface patterns, such as surface reconstruction of SiC electronic devices with novel designs, has been hindered by the chemical inertness of this material. State-of-the-art lithographic techniques with a number of dry-etching methods have been anticipated and are commonly used for controlling feature size, shape, and spacing of SiC devices. However, the available conventional lithographic techniques have a fundamental drawback in terms of cost, scalability, and process time. Therefore, patterning processes of SiC with an etch profile deeper than 1 μm remains a great technological challenge. In light of the considerable interest for SiC we were challenged to construct our sample using a focused ion beam (FIB) to pattern a SiC membrane without destroying the bulk optical properties, in such a way that SPP's can still be excited.

A focused ion beam has enough energy and momentum to remove material. With the patterning ability it is possible to structure a material in different geometrical shapes with good control of the shape and depth. The accuracy of this process and the material independency has permitted the application of this technique over a wide range of materials. FIB technique can be used in the creation process of a photonic array, where the regularity and the small size of the holes in the material, are crucial for the final functionality.

In this work we present a route for micromachining of SiC by a FIB. Microstructured SiC is of large current interest not only for photonic applications [20,21], and the results presented here can be of interest for many different applications. In the experimental part of this contribution the milling is specifically examined, with the intent to provide guidelines for selecting operating parameters for microstructuring of SiC. In the second part we exploit the properties of a photonic structure fabricated by a FIB. We show that SiC can be micromachined by a FIB, without destroying the optical properties, in such a way that SPP's can be excited.

2. Theory

It has been known for long, that a propagating quasi particle composed of a photon and a polarization wave is possible along the interface of two materials if the optical conditions are right [6]:

$$Re(\varepsilon_{\rm II}) < 0 \tag{1a}$$

$$|Re(\varepsilon_{\rm II})| > Re(\varepsilon_{\rm I}) > 0 \tag{1b}$$

where I and II indicate the two media, along the interface of which the surface polariton travels and ε is the complex frequency dependent dielectric function ($\varepsilon = \varepsilon(\omega)$). Eqs. (1a) and (1b) state that one of the materials must have a negative real part of the dielectric function at some frequency and the absolute value, for that frequency, must be larger than the corresponding value for the other medium. Equations for the excitation and propagation of surface polaritons can be derived from Maxwell's equations [6,22]. As mentioned above, if the polarization wave in the material is composed of electrons or phonons they are named surface plasmon polaritons or surface phonon polaritons (SPP). A surface polariton can only propagate close to the interface between two different media, and the amplitudes of the fields decay exponentially with the distance. The equation for the wave vector of a surface polariton [6] is

$$k_{\rm SP} = \frac{\omega}{c}\sqrt{\frac{\varepsilon_{\rm I}\varepsilon_{\rm II}}{\varepsilon_{\rm I}+\varepsilon_{\rm II}}} \tag{2}$$

where $k_{\rm SP}$ is the surface polariton wave vector, c the speed of light in vacuum, ω the angular frequency. In Fig. 1 the real part of the dispersion curve for a SiC/air interface is presented together with the light line for vacuum. The oscillator parameters for SiC are taken from [23] Surface polaritons are only non-radiative in the frequency interval where the dispersion relation is located to the right of the light line for the dielectric medium. This is because there is a momentum mismatch between SP's and incoming light. In order to excite the surface states, this mismatch must be added. Coupling of incoming light to the surface states can be done in three ways [6,24]. In this report the missing amount of momentum is added by a periodic surface structure with lattice constant a. The structure is a periodic array of circular holes, and the added k-vector is then $2\pi/a$.

Eq. (2) and Fig. 1 explain why the wavelength of SP's can become sub-wavelength and reach nano-scale for optical frequencies at the surface polariton resonance frequency. $k_{\rm SP}$ goes to infinity because $\varepsilon_{\rm I} + \varepsilon_{\rm II} \to 0$, which implies that the wavelength goes to zero. This behavior is the reason for the current interest in using SP's for high resolution microscopy.