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Ga_2O_3 microwires as wide dynamical range temperature sensors

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ABSTRACT

In this work, we present our recent results on the applicability of optical microcavities based on Cr doped Ga_2O_3 wires to operate as a nanothermometer in a wide temperature range (at least from 150 up to 550 K) and achieving a temperature precision of around 1 K. To this purpose, DBR (distributed Bragg reflectors) have been used to enhance the reflectivity at the lateral ends of the wires. The transduction mechanism encompasses both the luminescence features of the characteristic R-lines of Cr^{3+} ions in this host as well as the interferometric effects of the Fabry-Perot resonances within the cavity.

Keywords: gallium oxide, DBR microcavities, Cr ion levels, temperature sensor

1. INTRODUCTION

Gallium oxide has become a paradigmatic material able to work under extreme conditions due to its high chemical stability in combination with its superb physical properties. In addition, Ga_2O_3 micro- and nanowires are easily produced by thermal evaporation methods by oxidation of pure gallium, which add an extra value to the potential of this oxide. Regarding the optical properties, the ultra wide band gap of Ga_2O_3 allows optical transparency from the ultraviolet up to the near-infrared range, which makes it a very suitable host for optically active ions. This also allows tunable luminescence in a wide spectral range. Undoped Ga_2O_3 exhibits blue and UV emissions in 3.0 - 3.4 eV arising from native defects along with unintentionally impurities, as Si.[1,2] In addition, efficient emission in Ga_2O_3 doped with transition metal and rare-earth ions has also been reported for several applications.[3] One of the advantages of intraionic-related emissions in ionic hosts is that they show well defined and stable features that could be altered by their exposure to particular environments. In this sense, optical sensors for temperature have been designed by analyzing the optical response of the transition metal or rare-earth doped insulators.[4]

Beside the luminescence features, as intensity, lifetime, spectral shift or full width half maximum that characterize a specific emission line, optical thermometers based on interferometric properties in Fabry-Perot (F-P) cavities have also been proposed so far.[5] Ga_2O_3 micro- and nanowires wires have already been tested as efficient optical Fabry-Perot (F-P) microcavities to confine near-UV and near-IR light in undoped and Cr doped Ga_2O_3, respectively.[6] Reflectivities up to 70-80 % at the ends of the microcavities have been achieved by building a specially designed DBR (distributed Bragg reflectors) as mirrors in the F-P cavities. Both emissions are broad luminescence bands due to the electron-phonon coupling effects, which becomes an advantage for the wavelength fine tuning of the optical confined modes.

In this work, we present the capability of Cr doped Ga_2O_3 microwires, conveniently converted into optical DBR microcavities, as an excellent temperature sensor with a wide dynamical range, covering at least the 150 -

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550 K temperature range. The temperature precision is of around 1 K. The transduction mechanism encompasses both the luminescence features of the characteristic R-lines of Cr ions in this host as well as the Fabry-Perot resonances in the cavity.

2. EXPERIMENTAL

The optical cavities were built on Ga_2O_3 microwires obtained by thermal evaporation of metallic gallium and chromium oxide powders, as described elsewhere.[7] The structural and morphological characterization have been carried out by scanning electron microscopy (SEM) and micro-Raman spectroscopy in a confocal optical microscope. In selected Cr doped Ga_2O_3 wires, patterns of holes designed by finite-difference time-domain (FDTD) simulations were craved with the aid of a Focused Ion Beam (FIB) microscope in order to strongly improve reflectivity and delimit the optical cavity length, L. The simulations were performed using the OptiFDTD commercial software Optiwave. Micro-PL measurements were performed in two systems. For room temperature and above, a 325 nm He-Cd laser in a Horiba LabRam HR800 confocal microscope was used. On the other hand, a confocal system with the 488 nm line of an argon laser, an Olympus microscope with a 50x objective, a Super-Notch-Plus Filter, and a Peltier cooled CCD Synapse detector coupled to a Horiba monochromator, was used for both low and high temperature measurements.

3. RESULTS AND DISCUSSION

Thermal treatment at 1200 ºC for 8 hours of metallic gallium and chromium oxide powders placed onto a pellet made of Ga_2O_3 compacted powders lead to a huge amount of free-standing micro- and nanowires (Figure 1a). In order to keep the free-standing condition, the microwires were gently transferred to copper grids for further processing and characterization. Figure 1b shows a grid on which several wires have been dispersed. Most of these wires present a quasi-rectangular cross section with widths of few hundreds of nanometers to of about one micron and lengths up to several hundred microns, as it has been assessed by SEM. Room temperature (RT) micro-PL spectra from as-grown wires were used to identify the most promising wires to be converted into optical cavities in a next processing step. The incorporation of Cr ions in the octahedral sites of the Ga_2O_3 lattice gives rise to intraionic luminescence that can be explained in the framework of the configurational coordinate model.[7] The characteristic PL spectrum from Cr doped Ga_2O_3 is composed by sharp R lines and a broad emission band associated with the electron-phonon coupling in the lattice. R lines are quite prominent at low temperatures, while the broad band increases as temperature increases. Above RT, this broad band becomes the dominant one as R-lines lie underneath. Figure 1c shows the PL spectrum of one of the selected wires to build an optical nanothermometer that exhibit incipient resonant maxima overlapping the broad phonon-related band (marked with an arrow), besides the R-lines coming from Cr ions.

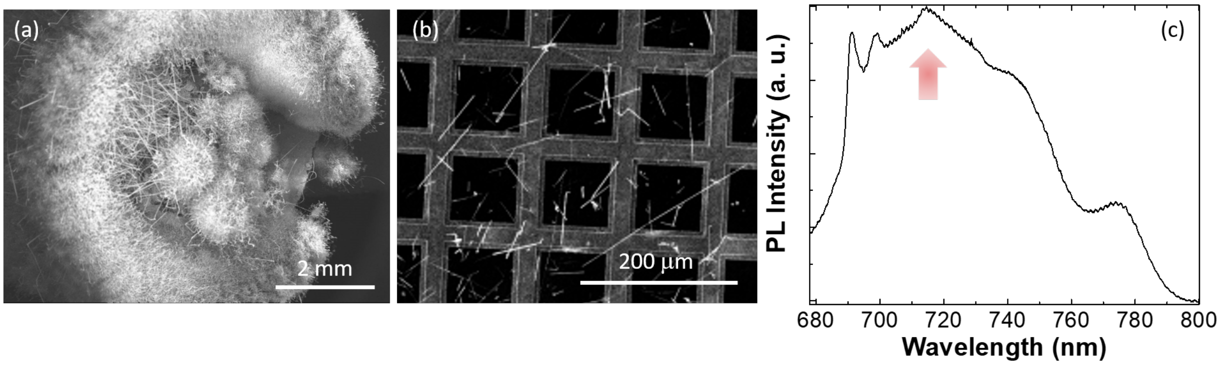

Figure 1. (a) SE image of Ga_2O_3 pellet after thermal treatment showing a high amount of nanostructures. (b) SE image of micro and nanowires on copper grid. (c) PL spectrum from one selected microwire showing incipient resonant maxima (marked with an arrow) overlapping the broad phonon-related band.

The geometrical features of the selected wires were used as input in the FDTD simulations to get the parameters data of DBRs with a stop band in the 680 - 750 nm region. The parameters needed to be defined are the cavity length, the number of holes, their size and pattern period. Afterwards, optical F-P cavities are made with the aid of a FIB that drilled the holes in the wires according to the output data of simulations. Figure 2a shows the SE image of one of the optical DBR microcavities, of length $L = 15\mu m$, delimited by two DBRs made of 10 rectangular holes of 183 x 385 nm^2, separated 200 nm each other. The process strongly improves the optical confinement of the red luminescence of Cr doped Ga_2O_3. This is due to the strong increase of the reflectivity values at the cavity ends, reaching values up to 78% in the 700-750 nm range. Figure 2b shows PL spectra collected at 140 K (blue line) and 400 K (red line) from the cavity shown in Figure 2a. The intense R-lines are clearly resolved at low temperature, even though a weak side-band with small resonances peaks is also observed. R-lines are still detected in the high temperature PL spectrum, and actually, they have been shifted to higher wavelengths. On the other hand, PL spectrum at 400 K displays sharp optical resonances, which have also been shifted with respect to their position in the 140 K PL spectrum, as it is highlighted by dots lines separated $\Delta\lambda_{FP}$, in Figure 2b. A more detailed evolution of the resonances shift from RT onward is presented in Figure 2c, for the main four F-P resonance peaks.

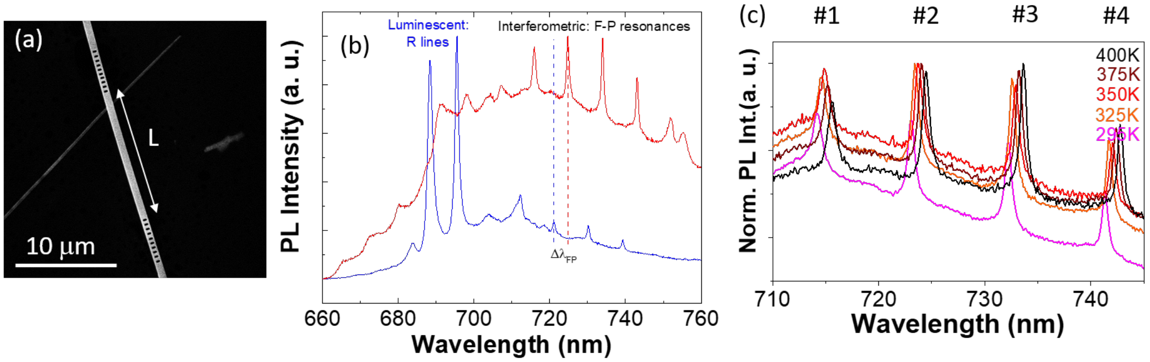

Figure 2. (a) SE image of a Ga_2O_3 patterned wire with a DBR cavity of length, L. (b) PL spectra collected at 140 K (blue line) and 400 K (red line). (c) PL spectra showing the shift of the F-P resonance peaks as temperature increases from RT up to 400 K.

Therefore, this system provides a thermometer under a dual approach that merges luminescence and interferometric transducing mechanisms in a robust material, as Ga_2O_3:Cr, which is crucial in applications. One of the advantages of this approach is the small scale of the device, which allows a minimal intrusive measurement of temperature. Another advantage comes from the wide dynamical range of operation, due mainly to the dual transducing mechanism. Luminescent thermometers based on the variation of observable quantities of the emission lines from optically active ions usually cover moderate temperature ranges, being more effective to operate in a low temperature regime. This is here applied to the temperature measurement through the shift of R-lines. However, the interferometric features are more pronounced at higher temperatures, even reaching several hundreds Kelvin, as Figure 2c shows. Therefore, the thermometer based on the F-P cavity built on Ga_2O_3:Cr provides a wide temperature range of operation in a single system. Finally, the fact that the observable quantity is an spectral shift of sharp emission lines ensures a good temperature sensitivity, thanks to the feasibility of achieving high spectral resolution in acquiring PL spectra. Details of the calibration curves that relate the maxima position for the resonances peaks with the temperature can be found in.[7] To assess the quality of the sensor, the temperature coefficients have been calculated for both R-lines and F-P resonances shifts. The temperature coefficient is defined as the ratio between the change in the observable quantity and the change of temperature. In this case, in the interferometric approach, the observable is the wavelength shift, $\Delta\lambda_{FP}$, hence the temperature coefficient would be: $\Delta\lambda_{FP}/\Delta T$ (nm/K). Figure 3 shows the trend of this parameter for resonance peaks 2 and 3 as a function of the temperature. The obtained values are in the order of 10 - 16 pm/K, which provide temperature resolution of around 1 K in the whole temperature range, by taking into account the accuracy of the experimental system in determining the wavelength positions.

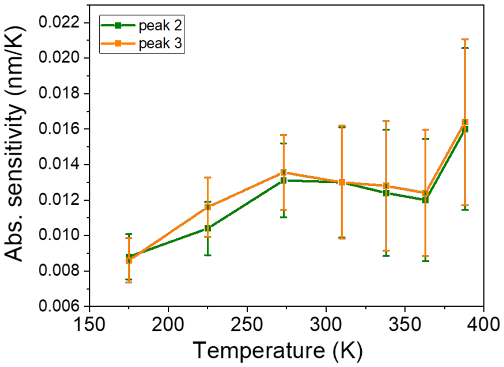

Figure 3. Sensitivity as a function temperature in the interferometric mode, taking the spectral shifts of two of the resonances maxima.

In summary, the demonstration of an optical temperature sensor based on stable Ga_2O_3:Cr microwires converted into DBR cavities is presented. To this end, the luminescence properties of Cr ions and the interferometric effects of optical modes confined in a Fabry-Perot cavity have been exploited. Both sharp intraionic R-lines and the positions of resonance maxima in the optical cavity are highly temperature sensitive through the electron-phonon coupling and the refractive index[8] of the material, which provokes spectral shifts in the emission lines. The fact that the observable quantity is the spectral shift of sharp emission lines favors the pretty nice temperature sensitivity achieved, of about 1 K. Besides, the designed optical cavity provides a wide dynamical range of operation, from cryogenic temperatures up to several hundred Kelvin, thanks to the merged luminescent and interferometric features.

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