Field Effect Transistors Deploying Anisotropic Two-Dimensional Materials for Light Generation and Detection

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Abstract: Three sets of Lorentz-Drude parameters are determined to describe anisotropic optical constants of ReS_2. Photodetector sensitivity and photoluminescence efficiency of ReS_2 coated SiO_2/Si substrates are studied. For ultra-thin applications, metal nanoparticles embedded in Si yield best performance.

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1. Introduction

In the last decade, transition metal dichalcogenides (TMDs) have received a significant interest due to our relatively new abilities to grow them in mono- of a few-layer forms. Researchers have shown that these two-dimensional (2D) materials can pave the way for new technologies in the areas of optics and opto-electronics. Field-effect transistors (FETs), photo-detectors, photo-emitting devices, tunable sensors are a few of the many 2D TMD based devices being studied [1–3].

Rhenium disulfide (ReS_2) differs from the other members of the TMD family due to two reasons: the inter-coupling between ReS_2 layers is weak [4] and ReS_2 is an anisotropic material [4, 5]. The former keeps ReS_2 as a direct band-gap material from bulk to monolayer [4] and the latter means that the interaction of light with ReS_2 changes not only spectrally but also spatially. These unique features of ReS_2 provide two additional degrees of freedom for the design of optical and opto-electronic devices deploying ReS_2: number of ReS_2 layers and orientation. Engineers can determine the optimum number of layers in order to have a certain amount of absorption, reflectance, transmission, or emission at a certain wavelength. Furthermore, they can utilize ReS_2 as a polarization-dependent platform for light emission or detection [1, 3].

This work starts with a discussion on a Lorentz-Drude model developed to represent anisotropic nature of ReS_2 both in analytical and numerical methods. After verifying its accuracy, the model is used for the analyses of light-emitters and light-detectors deploying thin films of ReS_2. By solving Maxwell's and circuit equations "almost simultaneously" with the finite-difference time-domain (FDTD) method, we first reproduce the experimental results found in the literature; then, we investigate how the performance of these devices can be improved with the surface plasmon resonance (SPR).

2. Anisotropic Model

Recently, anisotropic optical constants of ReS_2 have been extracted from the reflection spectroscopy measurements [3]. In this work, we fit these constants using three sets of Lorentz-Drude parameters obtained with MATLAB. These parameters yield a very accurate approximation of the extracted values. Then we calculate the reflectivity of ReS_2 coated SiO2/Si substrates analytically. Numerical results show an excellent agreement with experimental results, i.e maximum relative error is less 0.5 %.

3. Electromagnetic-Circuit Co-Simulation

Wavenology is a commercially available software package that can solve both for Maxwell's and circuit equations using the FDTD method. By placing a simple resistor between the S (source) and D (drain) gates in a typical FET geometry, where ReS_2 is placed in between those gates, the current induced by an external light source can be monitored, as it is done in photo-detecting experiments. Similarly, a voltage can be applied to different gates of the same structure and the intensity and frequency content of the emitted light can be monitored as it is done in photo-emission experiments. In the second step of this work, we analyze the performance of such structures both as an emitter and a detector, as functions of wavelength, polarization, gate voltage, and geometrical factors, i.e. thickness of the oxide and ReS_2 layers.

4. Improving Performance with SPR

Third and last step of this study aims to understand how we can increase the intensity of the light emitted by such devices using localized SPR phenomenon. We assume a gold nanoparticle array and try to determine optimum parameters (i.e. metal type, shape, dimensions, and inter-particle spacing) for maximum light emission from the ReS_2 film. This array can be fabricated on top the ReS_2 film, inside the SiO2 layer, or inside the Si substrate. For each scenario, the optimum parameters are determined with an analytical method called layered medium coupled dipole approximation (LM CDA) [6]. The accuracy of the results obtained with LM CDA is compared to numerical results obtained with Wavenology. These studies show that the third scenario, metal nanoparticle array inside the Si substrate, yields the maximum enhancement for thin oxide applications. A similar study on the performance improvement of ReS_2 based photo-detectors with SPR will be discussed at the conference as well.

5. Conclusion

An anisotropic Lorentz-Drude model is developed to define the optical constants of ReS_2 for analytical and numerical analyses. After verification of the model, opto-electronic analyses of ReS_2 based light emitters and photo-detectors are carried out. Numerical results show that substantial increase is achievable in these device's performance via plasmonic resonances.

References

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