Single-photon source based on NV center in nanodiamond coupled to TiN-based hyperbolic metamaterial

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Abstract: We experimentally demonstrate both the lifetime reduction and the enhancement of single-photon emission from nitrogen-vacancies in nanodiamonds coupled to a $TiN/Al_{0.6}Sc_{0.4}N$ superlattice. Our results pave the way towards future CMOS-compatible integrated quantum sources.

OCIS codes: (270.0270) Quantum optics; (270.5565) Quantum communications; (160.3918) Metamaterials

1. Introduction

Light sources able to deliver single photons on demand are the key to developing future quantum communication networks. Among available single-photon sources, nitrogen-vacancy (NV) centers in diamonds have recently gained significant attention, because they are well localized and stable against photobleaching at room temperature [1]. Many techniques have been proposed to enhance the emission rate of diamond NV centers using resonant photonic structures. Unfortunately, this approach is intrinsically limited in bandwidth and counteracts the broadband emission from diamond color centers. Coupling NV centers to hyperbolic metamaterials (HMM) allows for the spontaneous emission efficiency of single-photon emitters to be engineered over a broad spectral range [2]. This enhancement is a result of a drastic increase in the local density of states (LDOS) within an HMM, providing numerous extra radiative channels to the emitter. In addition, our superlattice structures make use of CMOS compatible materials, thereby opening new highways for the fabrication of integrated CMOS compatible single-photon sources.

2. Experimental set-up and sample details

Previously, we have shown that the emission from multiple NV centers in nanodiamonds can be enhanced over a broad range by multilayer hyperbolic metamaterials, fabricated as a stack of alternating layers of gold and alumina [3]. In this work, we extend our previous study towards the construction of an efficient on-chip single-photon source. The novelty of the current design was the use of a nanodiamond containing a single NV center which is coupled to a metamaterial based on titanium nitride (TiN). TiN is a new plasmonic material known for its CMOS compatibility, mechanical strength, and thermal stability at high temperatures [4]. A $TiN/Al_{0.6}Sc_{0.4}N$ superlattice was epitaxially grown on a [001]-oriented MgO substrate using reactive DC magnetron sputtering. The metamaterial consisted of forty alternating 5-nm-thick layers. The optical properties of the HMM were characterized using spectroscopic ellipsometry. The schematic of the experimental set-up is shown in Figure 1(a) where sample (NV centers coupled to the HMM) is depicted together with the fluorescence-lifetime imaging microscopy (FLIM) system used for its characterization. Nanodiamonds (Microdiamant AG) were spincoated on top of the HMM and covered with a thin protective layer of polyvinyl alcohol (PVA). The enhancement of the spontaneous emission rate and lifetime changes were investigated by time-correlated single photon counting (TCSPC) with a MicroTime200 (PicoQuant GmbH) and confocal microscope with NA = 1.3 oil immersion objective. A 532 nm 100 ps pulsed laser with an average power of ~0.2 mW and 20MHz repetition rate was employed. The single-photon nature of our source was verified by recording photon anti-bunching. For the latter experiment, the TCSPC setup was transformed into a Hanbury Brown-Twiss (HBT) interferometer with a CW 532 nm laser of similar average power as a pump source.

3. Results

Using the described system, we observed a significant dip in the second-order autocorrelation function ($g^{(2)}(0)<0.5$, Fig.1 (b)), which proves that the investigated system had only one NV center per nanodiamond and was performing as a true single-photon source. The TiN-based metamaterial exhibited hyperbolic dispersion ($\varepsilon_{\perp} = 15.14+i6.04$, $\varepsilon_{\parallel} = -1.47+i1.85$ at 685nm) in the wavelength range of the NV center emission (650-720 nm, Fig. 1(c), highlighted area). At the excitation wavelength (532 nm, Fig. 1(c), green line) the metamaterial behaved as a lossy dielectric ($\varepsilon_{\perp} = 2.36+i9.21$, $\varepsilon_{\parallel} = 1.47+i1.85$) providing a weak Fresnel reflection and therefore a high intensity of pump radiation at the surface. A four-fold reduction of the emission lifetime for the nanodiamonds deposited on the HMM surface vs. nanodiamonds deposited on glass coverslip was recorded as shown on Fig. 1(d). Simultaneously, a two-fold increase in emission rate was measured.

4. Conclusions

We have experimentally demonstrated that by coupling single NV centers to a CMOS compatible TiN-based HMM a considerable improvement in the performance of these emitters could be obtained. This makes them particularly promising for the development of future integrated CMOS-compatible single-photon sources.

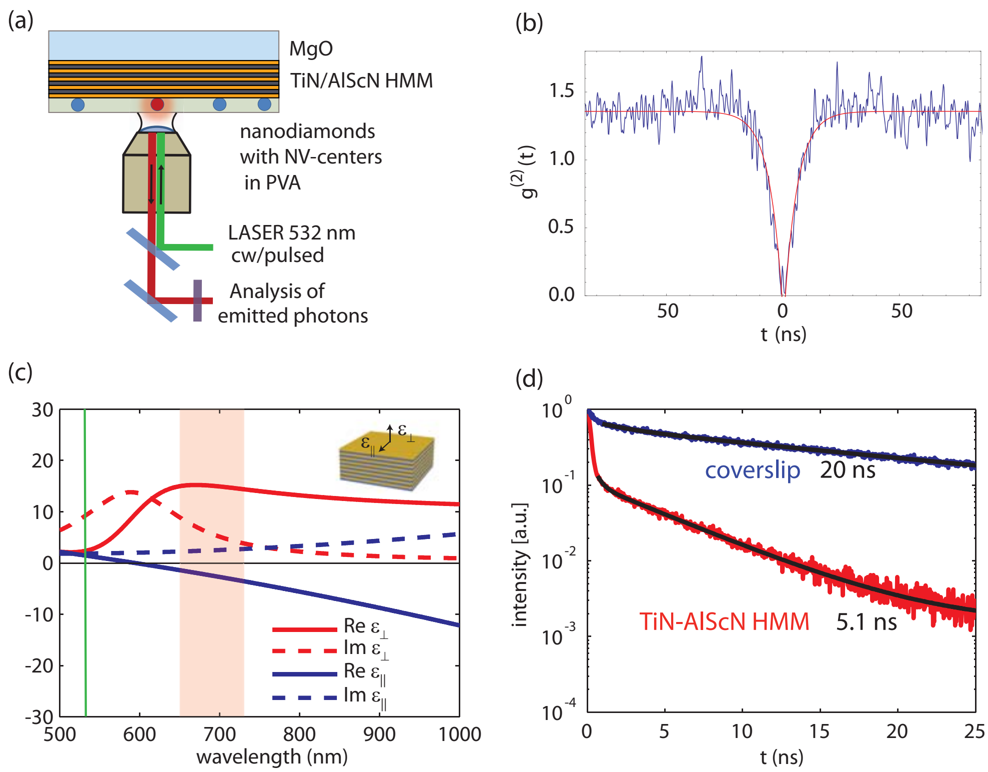

Fig. 1. Experimental setup and results. (a) Experimental setup and sample layout. Our HMM consists of forty alternating epitaxial layers of TiN and $Al_{0.6}Sc_{0.4}N$, (thickness of each layer – 5 nm) grown on a MgO substrate. Nanodiamonds containing NV centers were spin-coated onto the HMM and covered with 60-nm-thick PVA layer. (b) Second-order autocorrelation function for a representative nanodiamond with a single NV center in the vicinity of the HMM. The significant dip at zero time delay (g(2)(0)<0.5) indicates the single-photon emission. (c) Dielectric functions of the fabricated HMM obtained by spectroscopic ellipsometry in the spectral range 500 – 1000 nm. Within the range of the NV-center emission (650-720 nm-highlighted), the metamaterial shows hyperbolic dispersion ($Re[\varepsilon_{\perp}] >0$, $Re[\varepsilon_{\parallel}] <0$). At the excitation wavelength (532 nm, green line) the metamaterial behaves as a lossy dielectric. (d) Normalized fluorescence decays for a single NV-center located on glass coverslip (reference) and on HMM. Corresponding lifetimes of 20 ns (on coverslip) and 5.1 ns (on HMM) were extracted from the exponential fitting (black curves).

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