Tailorable Ultra-Thin Films and MXenes for Nanophotonic Applications

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With continuing advances in nanofabrication methods, the sizes of metal components in plasmonic devices have been shrinking, now approaching only a few monolayers in thickness. In ultra-thin plasmonic films, the strong confinement leads to the emergence of quantum phenomena, nonlocal effects and potentially enhanced nonlinearities. However, producing such thin films with noble metals is extremely challenging. Here, we present the recent developments on growing epitaxial quality, atomically flat, ultra-thin titanium nitride films that exhibit very good metallic/plasmonic properties, comparable with their bulk counterparts. The potential of these films for extreme light confinement and electrically controlled structures will be discussed.

We have experimentally demonstrated the growth of epitaxial quality, ultrathin TiN films (< 10nm) with sub nm roughness exhibiting metallic properties. These metal films would play a crucial role in the realization of dynamic electrical control of optical properties as well as in probing the theoretical predictions on the breakdown of atomic selection rules. Together with its refractory properties and CMOS compatibility, ultra-thin TiN shows great promise for realizing various quantum and nonlocal nanophotonic applications.

Another direction in emerging photonic materials is novel two dimensional (2D) materials. MXenes are a large family of 2D nanomaterials formed of transition metal carbides, nitrides and carbonitrides, many of which show high metallic conductivity, surface hydrophilicity and excellent mechanical properties. They are usually derived from layered ternary carbides and nitrides known as MAX (M_{n+1}AX_x) phases by selective chemical etching of the ‘A’ layers and addition of surface functional groups ‘T’ (-O, -OH or -F), making the final composition of M_{n+1}X_nT_x. This study is motivated by the limited exploration of this new material class of growing interest, in the area of nanophotonics and plasmonics.

We present a random metamaterial constructed by dispersing monolayer Ti_3C_2T_x nano sheets into the gain medium for lasing application. Emission from the device under optical pump shows that sharp peaks start to emerge from the broad-band background at a threshold value of ~ 0.54 µJ/pulse. With increasing pump energy, other sharp peaks appear, which is consistent with the behavior of random lasing achieved through coherent feedback. The lasing behavior in this metamaterial can be controlled by changing the density of the Ti_3C_2 in solution. With increasing density of Ti_3C_2T_x, the optical response of the metamaterial is enhanced, thus making it easier to form lasing modes.

Localized surface plasmon type resonances have also been demonstrated in nanostructured films made from aqueous dispersion of 2D Ti_3C_2T_x nanosheets. A planar design of highly broadband plasmonic absorber is implemented as an application of this new plasmonic material. Aqueous dispersion of 2D sheets of MXene (with lateral dimension of 1-2µm) was spin coated and dried in nitrogen to form a continuous film on desired substrate. Using the measured optical properties of these spin-coated films, we performed numeric simulations of Ti_3C_2T_x disks/pillar-like structures showing strong signatures of localized surface plasmon type resonances in the NIR, tunable with varying dimensions. These resonances were then optimized for the design of the absorber with maximum efficiency in the NIR. This simple nano-disk array (diameter & thickness of 0.4 µm) enables ~80% absorption across ~0.5-1.6 µm. The spin coated films were patterned into disk arrays using electron beam lithography and dry plasma etching process and the absorption was experimentally measured using spectroscopic ellipsometry technique.