Advancements in nanoscale coherent emitters: The development of substrate-free surface plasmon nanolasers

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Abstract

We have developed a substrate-free surface plasmon polariton laser to address the challenges associated with confining electromagnetic fields for integrated optoelectronic circuits at the nanoscale. Traditional plasmonic structures, such as nanoshell-based lasers, demonstrate potential for the detection of subcellular structures; however, they suffer from high plasmon dephasing rates and elevated thresholds, which significantly hinder their integration potential. An alternative approach involves a propagating surface plasmon laser based on a layered semiconductor–insulator–metal configuration, which facilitates electrical excitation but necessitates a bulky supporting substrate, thereby limiting its applicability in bio-related contexts. Our substrate-free design, featuring direct contact between the film and air, markedly reduces the laser threshold while maintaining performance across various surfaces. This innovation presents a promising pathway towards the realization of miniaturized, bio-integrated optoelectronic devices.

Substrate-free structure and simulation

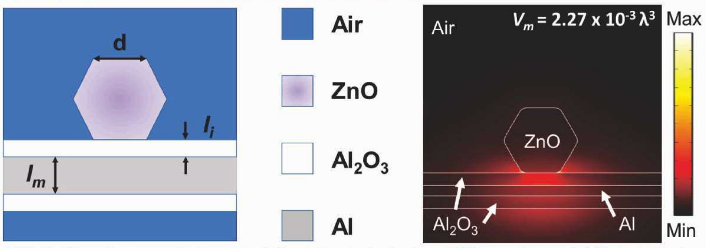

FIG. 1. Structures and characteristics of substrate-free SPP nanolaser: (a) Substrate-free SPP nanolaser structure, with a ZnO nanowire placed on a thin film. (b) The magnitude of |E(x, y)| for the theoretical minimum substrate-free SPP structure at a wavelength of 373 nm, illustrating the confinement of the electric field within the Al_2O_3 layer

Fabrication of substrate-free SPP laser

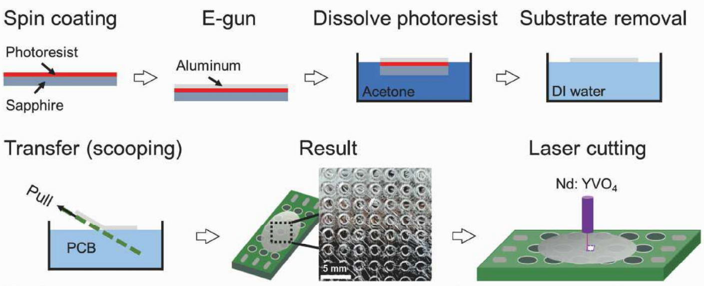

FIG. 2. Wet transfer process of substrate-free ZnO surface plasmon nanolaser. The schematic illustrates the thin film suspended on the PCB and the cross section of the substrate-free ZnO nanolaser.

Material analysis

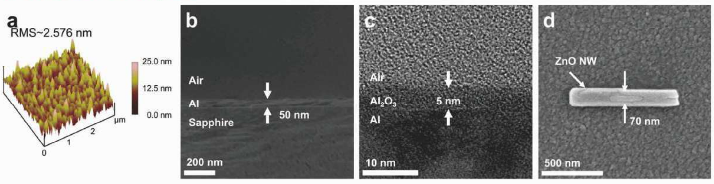

FIG. 3. Surface quality of the substrate-free ZnO SPP laser. (a) AFM image of a 50-nm thick Al film grown on a sapphire substrate in a 3 ×3 μm² (b) SEM image of Al thin film. (c) TEM image of the Al thin film cross section. (d) Top view SEM image of the ZnO nanowire laid on the Al film.

Reference

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Optical properties of substrate-free nanolaser

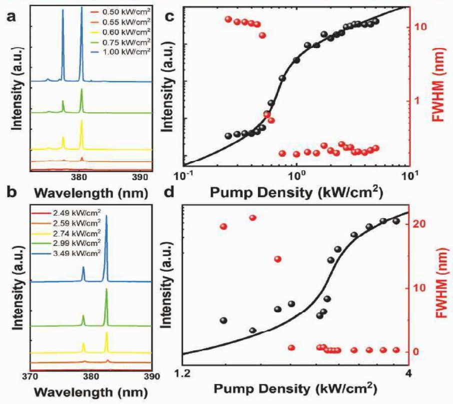

FIG. 4. Lasing characteristics of substrate-free ZnO SPP nanolaser. (a) and (b) Spectrum of an 830-nm long ZnO nanowire on an Al film, pumped and suspended post transfer to a Si substrate. The threshold values for (a) and (b) were ~1.38 and 2.56 kW/cm2, respectively. (c) and (d) Corresponding L–L curves (black spheres) and linewidths of dominant peaks (red spheres) of (a) and (b). The extracted spontaneous coupling factors (β) of (c) and (d) were 4×10^{-3} and 1×10^{-3}, respectively.

Statistics of threshold and changing temperature

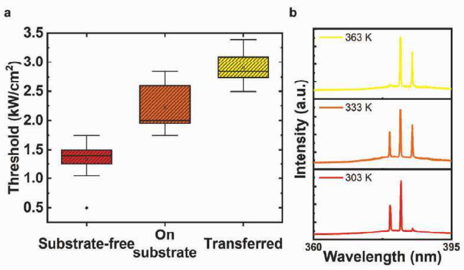

FIG. 5. (a) Quarter box chart illustrating the 13 nanowire samples under three conditions: substrate-free, with substrate, and transferred to a silicon substrate, which had average thresholds densities of 1.32, 2.22, and 2.90 kW/cm², respectively. (b) Evolution of the lasing spectra as the temperature increased to 363 K.

Conclusion

In conclusion, we have developed a substrate-free surface plasmon polariton laser with a reduced threshold and compact mode volume. This design enhances field confinement and demonstrates high-temperature operability, making it suitable for integration into practical optical circuits. The transferability of the nanolaser facilitates various applications, including biosensing, ultra-fine laser displays, and nanophotonics, thereby presenting significant potential for advancements in optical communications and on-chip interconnects.

Full Paper

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