Gallium nitride for ultrasensitive thermo-active switching in terahertz metamaterial micro–nanophotonic devices

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Supporting Information

1. Experimental Section

Sample Fabrication:

The GaN metamaterial was fabricated in three steps. A 5 μm thick polyimide film was first spin-coated onto a 300 μm thick SiO_2 substrate and then baked for approximately five hours at a specified temperature. The photoresist-coated sample was then aligned with a mask plate on a lithography machine and exposed to ultraviolet light. Next, the samples were placed into a magnetron sputtering system, thus completing the preparation of 0.2 μm thick aluminum structural units. Finally, the fabrication of the GaN metamaterial was completed by vaporizing a 130 nm-thick GaN layer onto the proposed metamaterial.

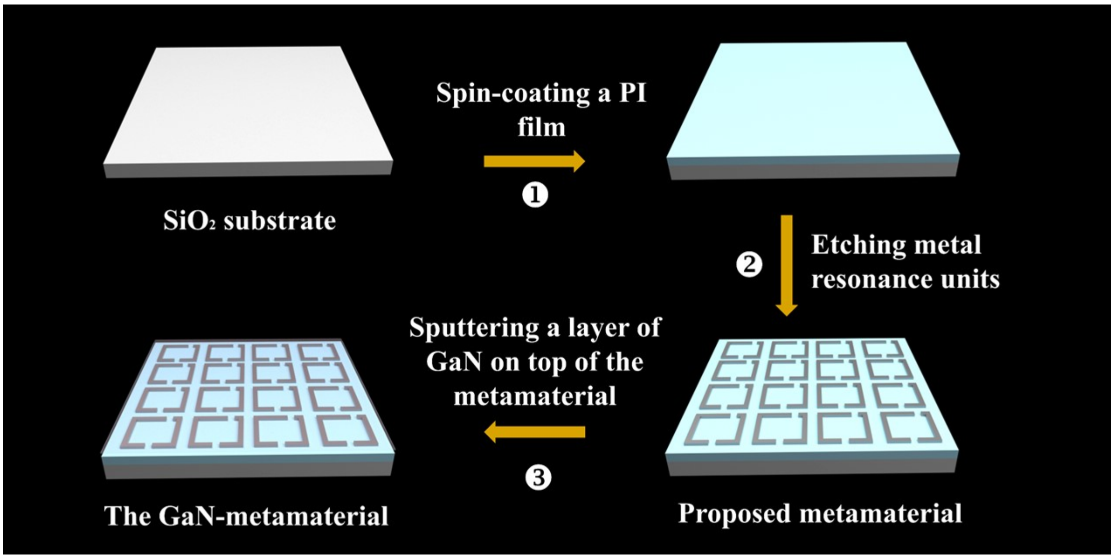

Fig. S1. Specific fabrication processes for GaN metamaterial.

Simulation:

We performed extensive numerical simulations of GaN metamaterials using computer simulation technology (CST) and COMSOL Multiphysics simulation packages. Perfectly matched layers were used in the top and bottom domains. The proposed hybrid GaN metamaterial was vertically illuminated by a THz wave with an electric field along the *y*-direction (E_y) and a magnetic field along the *x*-direction (H_x). The metamaterial microstructures were made of lossy aluminum metal, and the conductivity was set to be $\sigma_{dc} = 3.56 \times 10^7 S/m$. Polyimide was used as the flexible substrate, and the dielectric constant and tangent loss were 3.4 and 0.05, respectively. The dielectric constant of GaN was set to be 9, and to study the active thermal switching characteristics of the GaN metamaterial, the conductivity σ of GaN was set as the experimentally retrieved conductivity of the GaN epitaxial layer at different temperatures.

2. The detailed introduction of the heating rate and cooling rate of the heating plate

The proposed GaN-based metamaterial is excited by a thermal signal generated by a digital heating table (model: ST700), which results in amplitude and phase modulation of the incident terahertz wave. The heating and cooling rates of the hot plate are key parameters of its functionality. The heating rate ranges from 1 to 5 degrees Celsius per minute, depending on the surrounding environment. Similarly, the cooling rate typically falls within this range, ensuring that materials can return to baseline temperatures without causing thermal shock or structural damage. These rates are precisely calibrated to maintain the integrity and performance of GaN-based metamaterials, as rapid temperature changes can induce material stress and potential failures. The digital hot plate used in this experiment is equipped with a high-precision temperature sensor and a digital display, allowing for real-time monitoring and precise control of the plate's temperature. The temperature adjustment precision is high, usually accurate to 0.1°C. Additionally, this digital hot plate can maintain a stable set temperature, minimizing fluctuations and ensuring the stability and repeatability of the experimental process.

3. The effect of structural parameters of metamaterial cells on Fano resonance

The structural parameters of the metamaterial unit cell, such as the periodicity (*p*) and the opening spacing of the resonant ring, *w*, play a crucial role in determining the characteristics of the observed Fano resonance and its modulation. Variations in periodicity affect the coupling between the resonant modes and the surrounding medium, which influences the resonance frequency and its sharpness. Similarly, changes in the opening spacing of the resonant ring impact the strength and quality factor of the resonance, thereby modifying the Fano resonance profile and its modulation depth. The opening spacing of the resonant ring, *w*, during the preparation of the Al structure may differ from the simulation results due to the limitations of the fabrication process. Hence, we investigated the effect of *w* on the metarsurface transmission coefficient as well as on the Fano resonance. Figure. S2 (a) shows that *w* = 4 μm increases to *w* = 8 um, the transmission curve does not significantly change except for a slight shift in the resonant frequency position and a slight increase or decrease in the transmissivity. Similarly, we also investigated the effect of fabrication deviation of the period *p* on the Fano resonance. Figure. S2 (b) depicts that when *p* = 96 μm is increased to 102 μm, i.e., the fabrication error ranges from -4% to +4%, there is no significant change in the transmittance curve of this metamaterial, with only slight shifts in the resonance frequency position and slight increases or decreases in the transmittance. Therefore, the Fano resonance and its modulation performance can be maintained at a high level throughout the deviation range, and the GaN metamaterial modulator maintains good robustness over a wide range of fabrication errors.

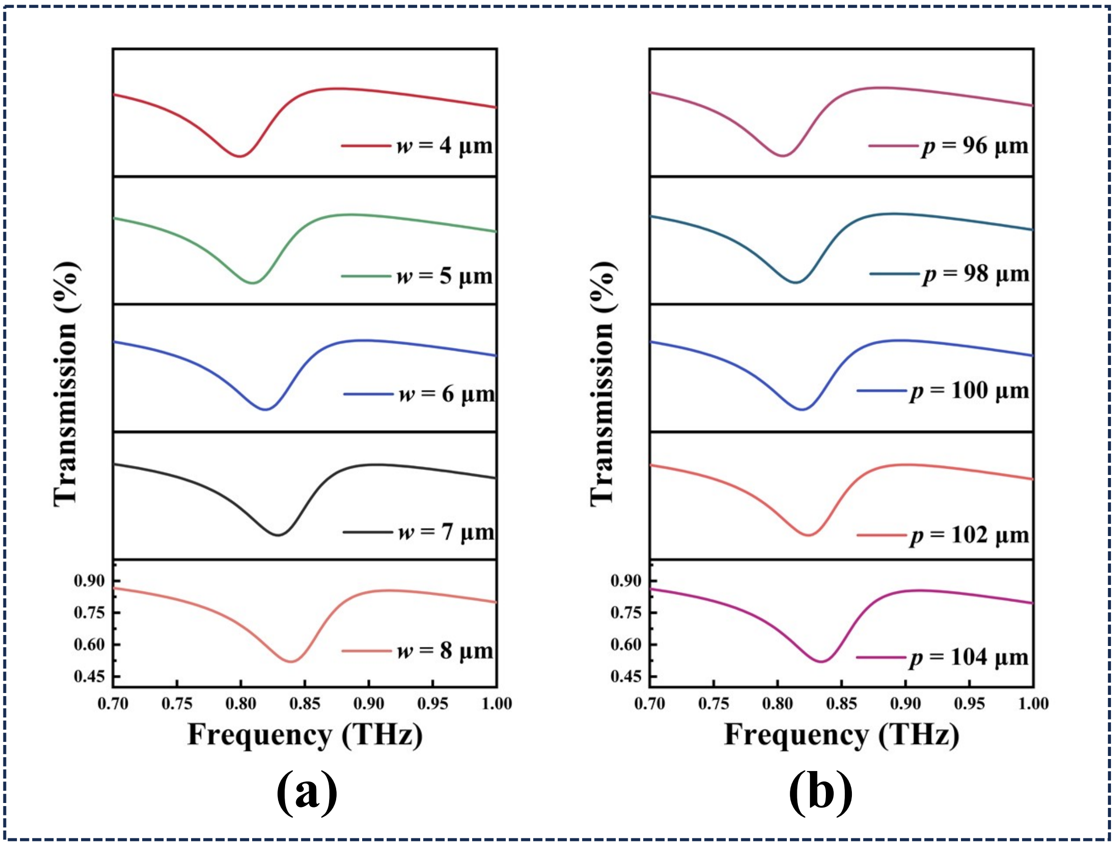

Fig. S2. The effect of structural parameters of metamaterial cells on Fano resonance. (a) and the opening spacing of the resonant ring, *w* (b) the periodicity, *p*.

4. The function of polyimide film in this GaN device

Polyimide exhibits excellent thermal stability and resistance to high temperatures. In metamaterial modulators, which often operate under conditions that generate significant heat, polyimide helps manage thermal loads effectively. This thermal stability ensures that the device maintains consistent performance and reliability, even under prolonged operation or in harsh environments. It prevents thermal degradation of the device components, thereby extending the device’s lifespan and maintaining its functionality over time. Additionally, polyimide is known for its superior chemical resistance, which protects the metamaterial modulator from environmental damage and corrosion. Moreover, polyimide thin films offer excellent dielectric properties, which are vital for the modulation of electromagnetic waves. In the context of a metamaterial modulator, the polyimide layer can help in tuning the device’s electromagnetic response by acting as an insulating layer that supports the precise arrangement of the aluminum metal structures and the semiconductor layer. This dielectric property is crucial for maintaining the integrity of the modulated signals and ensuring high efficiency and accuracy in the device's operation.