Nonlinear Analysis of HEMT Inspired GaN Optical Waveguide under Thermal Stress

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***Abstract*—We present a study introducing a novel approach to augment nonlinearity within high electron mobility transistor (HEMT) inspired optical waveguides. This study involves the AlGaN/GaN/AlN layers on both silicon carbide (SiC) and sapphire substrates. Our primary objective is to conduct a comprehensive nonlinear analysis of these structures using the finite element method (FEM) while considering thermal stress. A key aspect of our investigation centers on optimizing light interaction under varying thermal stress conditions. By manipulating core and cladding parameters, we achieve heightened nonlinearity within the temperature range of 27°C to 600°C.Our findings reveal an intriguing outcome: the HEMT inspired waveguide integrated on a sapphire substrate exhibits notably enhanced nonlinearity compared to its SiC substrate counterpart. These results hold significant promise of considering the thermal stress parameter for future on-chip GaN-based quantum photon pair generation applications.**

***Index Terms*—HEMT, Nonlineatity, SiC, and Sapphire**

I. Introduction

GaN-based HEMT devices have gained significant attention due to their wide bandgap, high field strength, and superior mobility. These attributes result in lower power consumption and improved stability, enabling the devices to be compact [1], [2]. Additionally, the successful integration of electronic-photonic configuration (III-N) materials with CMOS compatibility has led to the development of ultra-small packages. These packages feature a single chip containing a light source, modulators, and detectors, functioning similarly to electronic devices [1], [2]. These functionalities are used for signal processing, quantum optics, ultra-low power optical switching, sensing, and notably, nonlinear optics. Using a spontaneous four-wave mixing process, on-chip GaN-based quantum photon pairs are generated efficiently with lesser pump power using a microring resonator [3]. Even photon pairs generated efficiently, controlling the temperature is tedious process to make stable and eventually due to thermal mismatch between the layers causes the thermal stress. This thermal stress induces the refractive index profile change of the whole optical waveguide due to the thermo-optic and elasto-optic coefficients.For a 100°C temperature scale, the refractive-index change is of the order of 10^{-2}, which is one order of magnitude higher than that caused by stress. So, thermal stress changes continuously alter the optical parameters such as dispersion and non-linearity. For the HEMT-inspired GaN optical waveguide structure with different substrates like SiC and Al_2O_3, nonlinearity studies under different thermal stress are not yet discussed in detail. In this article, studying the non-linearity characteristics of HEMT-inspired optical waveguides with thermal stress will be useful in future on-chip quantum photonic generation applications.

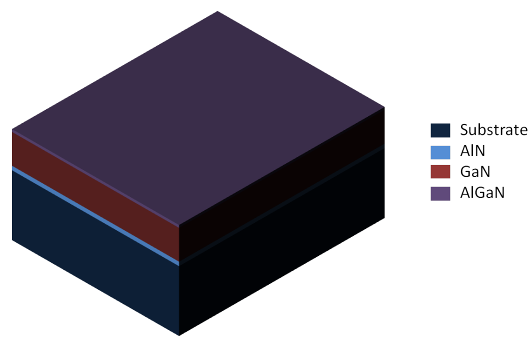

Fig. 1. The cross-section of the HEMT-inspired GaN optical waveguide

II. Proposed HEMT inspired GaN optical waveguide

The proposed HEMT-inspired GaN optical waveguide consists of two substrates: SiC and Sapphire. We consider both

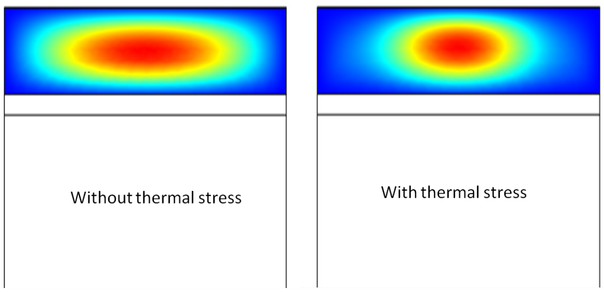

Fig. 2. electric field distribution of the HEMT-inspired GaN optical waveguide, both without and with thermal stress, on a SiC substrate.

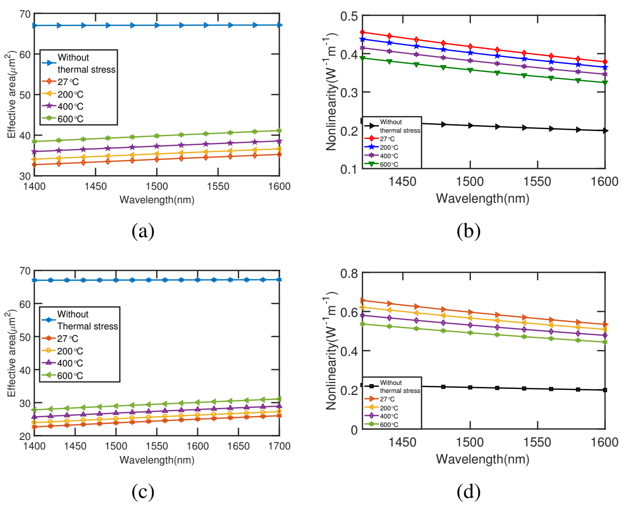

Fig. 3. **Sapphire**: (a)The effective area and (b) nonlinearity **SiC**: (c)The effective area and (d) nonlinearity changes under different thermal stress

these optical waveguides to have the same slab Waveguide parameters for the nonlinearity study under different thermal stresses. The wavelength-independent refractive index profile, thermo, and elastic optic coefficients are well-studied in our previous research [1], [2]. The HEMT-inspired GaN waveguide features an AlN layer with a thickness of 90 nm, a core thickness(GaN) of 5μm, and a top layer of $Al_{0.23}Ga_{0.77}N$ with a thickness of 30 nm. The cross-section of the HEMT-inspired GaN optical waveguide is shown in Fig.1. The simulation is carried out using COMSOL Multiphysics Waveoptics and structural mechanics module with various thermal stresses from room temperature to 600°C. After applying thermal stress, the mode profile of HEMT-inspired GaN waveguide mode is confined in the middle of the waveguide and leads to higher confinement, and eventually, the nonlinearity will suit ups. The Electric field distribution of SiC-based GaN waveguide mode profiles is shown in Fig.2 without and with thermal stress.

The effective area completely depends upon the waveguide dimensions. If the effective area of the GaN optical waveguide increases, the nonlinear parameter decreases and vice versa. The effective area is calculated by using the below formula [4],

$$A_{eff} = \frac{(\int\int_{-\infty}^{\infty} |F(x,y)|^2 dxdy)^2}{(\int\int_{-\infty}^{\infty} |F(x,y)|^4 dxdy)}, \tag{1}$$

The nonlinear parameter is based on the intensity-dependent RI (n_2) and effective area A_{eff}. The nonlinear parameter is calculated by the following formula [4]:

$$\gamma = \frac{2\pi}{\lambda}\frac{n_2}{A_{eff}}. \tag{2}$$

Where n_2 of GaN is 7.8×10^{-19} m^2/W [5] and λ is a wavelength. We begin our simulation with room temperature and increased rapidly upto 600°C for the SiC based GaN optical waveguide. The effective area increases as thermal stress rises. Conversely, nonlinearity also varies with thermal stress. The changes in effective area and nonlinearity across different thermal stress levels are shown in Fig.3(a) and 3(b) . The same trend happens for sapphire based GaN optical waveguides, interestingly using sapphire based HEMT inspired GaN optical gives high nonlinearity due to the high thermal mismatch between the layers(See Fig.3(c) and 3(d)).

III. Conclusion

In this paper, we have demonstrated the tunability of nonlinearity under thermal stress for HEMT-inspired GaN optical waveguides on SiC and Sapphire substrates. The results indicate that Sapphire-based optical waveguides exhibit higher nonlinear values due to greater confinement. This study reveals that the importance of considering the thermal stress parameter for future on-chip GaN-based quantum photon pair generation applications.

IV. Acknowledgement

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