Aluminum Nitride Photonics Platforms on Silicon Substrate

Nanxi Li[1], Chong Pei Ho[1], Yanmei Cao[2], Shiyang Zhu[1], George F. R. Chen[2], Yuan Hsing Fu[1], Yao Zhu[1], Dawn T. H. Tan[2], and Lennon Y. T. Lee[1]

*[1]Institute of Microelectronics, A*STAR (Agency for Science, Technology and Research), 2 Fusionopolis Way, 138634, Singapore*
[2]Photonics Devices and Systems Group, Singapore University of Technology and Design, 8 Somapah Road, 487372, Singapore
Email address: linx1@ime.a-star.edu.sg

Abstract: The CMOS-compatible AlN photonics platforms developed within Institute of Microelectronics (IME) are presented, and nonlinear index of the AlN is reported. The photonics devices demonstrated are reviewed, and the future prospective is provided. © 2021 The Author(s)

OCIS codes: (230.3120) Integrated optics devices; (130.3130) Integrated optics materials.

1. Introduction

Aluminum nitride (AlN) has been widely studied in complementary metal oxide semiconductor (CMOS)-compatible integrated photonics platform contributed by the following advantages. Firstly, compared with other photonics materials such as silicon (Si), silicon nitride (Si_3N_4), and silicon dioxide (SiO_2), AlN has relatively large bandgap (6.2 eV) and wide transparency window (from ultra-violet to infrared) [1]. Secondly, the relatively high refractive index compared with SiO_2 makes it suitable for optical waveguide [2]. Thirdly, AlN has significant 2nd order nonlinear effect and also 3rd order nonlinear effect, which can be used for optical modulator [3] and optical frequency comb generation [4]. Fourthly, AlN has high thermal conductivity (K = 285 $Wm^{-1}K^{-1}$) and low thermal-optic coefficient ($dn_{AlN}/dT = 2.32\times10^{-5}\ K^{-1}$) [5], which enables the handling of high optical power. Lastly, it has piezoelectric effect, which makes it suitable for photon-phonon interaction and enables the modulation of microwave frequency on optical signal [6].

Here, the development progress of CMOS-compatible AlN photonics platforms on 200-mm wafers in Institute of Microelectronics (IME) are presented. The nonlinear index of the AlN is obtained and reported. The photonic devices demonstrated are reviewed and summarized. The future prospects of the development are also included.

2. AlN-based photonics integrated circuits fabrication platforms

In this section, we present the fabrication process flow developed in IME for both passive and active AlN photonics integrated circuits, and also report the measured nonlinear index of the AlN film. Standard CMOS back-end process has been used to fabricate AlN-based photonics devices on Si. Fig. 1(a) shows the process flow for passive devices. Starting from Si wafer covered with SiO_2 layer (a-I), a layer of AlN is deposited via sputtering deposition, followed by a layer of SiO_2 deposited on top as hard mask for patterning and etching of AlN layer (a-II). After that, a layer of SiO_2 is deposited on top, followed by a chemical mechanical polishing (CMP) process to flatten the top surface (a-III). An annealing process at temperature range between 500 to 1000 ^{o}C can be applied to reduce the AlN waveguide propagation loss. The fabricated 8-inch wafer with passive AlN photonics integrated circuits is illustrated in Fig. 1(b).

The active fabrication process flow is illustrated in Fig. 1(c). Starting from Si wafer covered with SiO_2 layer (b-I), a layer of titanium nitride (TiN) or doped Si is deposited and patterned as bottom electrodes (b-II). After that, a layer of SiO_2 is deposited on top, followed by a CMP process. A layer of AlN is deposited and patterned in the same way as for passive waveguide (b-III). After opening the contact holes for bottom electrodes, Al is deposited on top followed by a patterning process (b-IV). After one more round of SiO_2 cladding deposition and CMP, both top and bottom electrodes are opened for contact (b-V). Although the CMOS-compatible fabrication process flow for both passive and active AlN photonics circuits are demonstrated on 8-inch wafers, these fabrication processes are scalable to larger 12-inch wafers, which can further bring down the fabrication cost for mass-production.

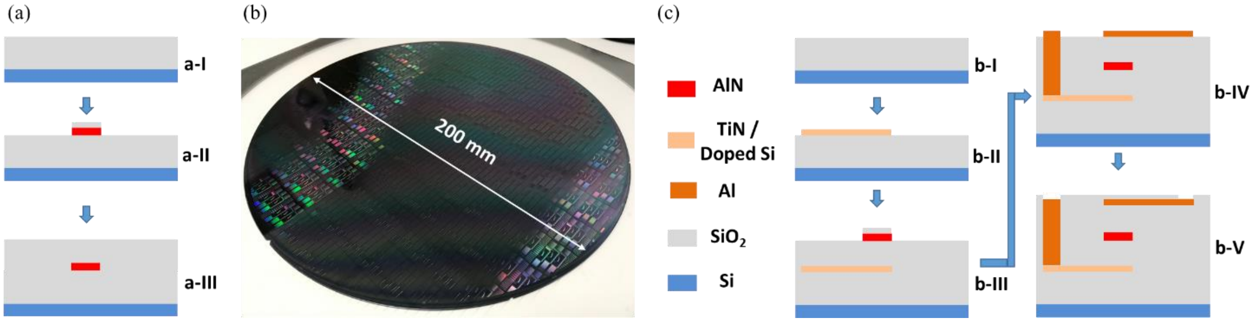

Fig. 1 (a) Fabrication process of passive AlN integrated photonics circuits on 8-inch silicon wafer. (b) Fabricated 8-inch wafer with passive AlN integrated photonics circuits. (c) Fabrication process of active AlN integrated photonics circuits on 8-inch silicon wafer.

To measure the nonlinear index of the AlN for nonlinear applications, self-phase modulation (SPM) experiment is conducted on passive AlN waveguide without layers for active tuning. Fig. 2(a) shows the optical image of the fabricated AlN waveguide. It has designed width of 1 µm, height of 0.5 µm, and length of 4.4 cm. This waveguide is tested using the setup with schematic illustrated in Fig. 2(b). A mode-locked femtosecond fiber laser with a pulse width of ~1.4 ps and repetition rate of 20 MHz is used as light source, and optical spectrum analyzer is used to monitor the spectrum broadening of incident pulse due to SPM. The captured spectrum is shown in Fig. 2(c). The nonlinear refractive index of the AlN film is extracted to be $(2.5\pm0.99)\times10^{-19}$ m^2/W, by modeling the SPM results using the generalized nonlinear Schrödinger equation (GNLSE) with the waveguide nonlinear parameter γ as a fitting parameter.

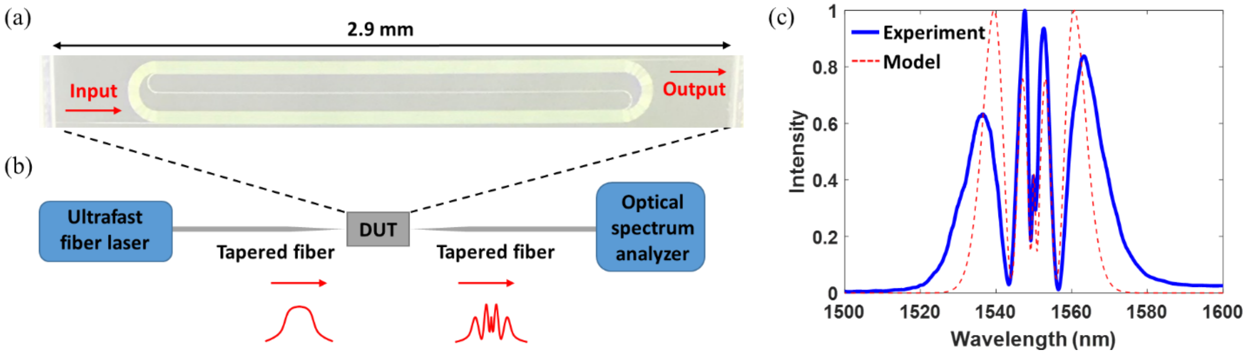

Fig. 2 (a) Optical image of fabricated AlN waveguide for self-phase modulation (SPM) experiment. (b) Schematic of SPM experiment setup. DUT: device under test. (c) Measured and modelled SPM spectrum after AlN waveguide.

3. Integrated optical devices on AlN-based photonics platforms

In this section, the integrated optical devices demonstrated on IME AlN photonics platforms are reviewed and summarized. In 2016, optical modulators based on IME's active AlN photonics platform have been demonstrated [7]. The optical modulator works based on the Pockels effect of AlN, which is the 2nd order nonlinear effect. As shown in the fabricated cross section illustrated in Fig. 1(c), the top and bottom electrodes are placed above and below the AlN to maximize the electric field through the AlN waveguide and hence optimize the electric-optic overlap. Optical modulators with microring and Mach–Zehnder interferometer (MZI) structure have been reported in [7]. The MHz-level modulation of MZI modulator is demonstrated. Furthermore, in the follow-up work reported in 2019 [2], a push-pull structure has been used for optical modulator, which is able to reduce the V_π of the MZI by half. V_π of 21 V has been reported for MZI modulator working at communication wavelength [2]. Also, in the same year (2019), the passive photonics devices, including waveguide, directional coupler, interferometer and microring resonator, have been demonstrated working at mid-infrared (MIR) wavelength range, covering from 3660 nm to 3900 nm [8]. The waveguide loss in MIR is reported to be 0.8 dB/mm after proper annealing process on passive AlN-based platform.

4. Conclusion

To sum up, the CMOS-compatible integrated AlN photonics platforms on Si developed in IME are presented. The nonlinear index of the AlN is obtained to be $(2.5\pm0.99)\times10^{-19}$ m^2/W. The functional devices based on the AlN platforms are reviewed and summarized. The future work includes the development of photonics platform using Scandium (Sc) doped AlN [9], and exploration of potential superior nonlinear optical properties of ScAlN, due to the increased non-central symmetry of the crystal structure.

The authors acknowledge the Agency for Science, Technology and Research, Science and Engineering Research Council (SERC) Strategic Fund: NOVEL-PAT (Grant no. A19B3a0008).

5. References

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