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研究課題名（和文）Development of Ge-based mid-infrared waveguide platform with strong optical confinement for on-chip gas sensing

研究課題名（英文）Development of Ge-based mid-infrared waveguide platform with strong optical confinement for on-chip gas sensing

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研究成果の概要（和文）：本研究では、超高感度を持つオンチップガスセンシングに向けて、Si基板上に中赤外光デバイスプラートフォームを開発した。まず、分子線エピタキシー法と成長後アニールを用いて、超低中赤外吸収(<10 cm-1)のGe-on-Si薄膜を結晶成長した。次に、光導波路、ファイバーへのグレーティングカプラー及びマイクロディスク共振器等の基本光素子をGe-on-SiとSOI基板上に実現した。特に、10%超えたファイバーと導波路のカプリング効率が得られた。また、理論計算により、これらのデバイスをベースして、0.04 mm2未満のチップ領域でメターオーダーの等価光吸収長さが得られることはわかった。

研究成果の学術的意義や社会的意義
The research indicates that the proposed MIR photonic platform is very promising for high sensitivity on-chip trace gas sensing, and represents a new direction for group-IV photonics. It thus pave the way to low-cost, practical, portable, and smart gas monitoring tools in industry and daily life.

研究成果の概要（英文）：In this research, silicon-based mid-infrared (MIR) photonic platform has been developed for ultra-sensitive on-chip gas sensing. Ge-on-Si films with ultralow MIR absorption of less than 10 cm-1 have been grown by molecular beam epitaxy and post annealing. Fundamental building blocks, including optical waveguides, fiber-to-waveguide grating couplers, and microdisk resonators, have been realized on Ge-on-Si and silicon-on-insulator substrates. A MIR waveguide transmission measurement system has been established and high coupling efficiency over 10% between fiber and waveguide has been realized. Based on these device components, sensitivity analysis indicates that ultra-long effective optical absorption length on the order of meter can be readily achieved on-chip within device footprint of less than 0.04 mm2.

研究分野：半導体工学

キーワード：Mid-infrared photonics　Silicon photonics　Gas sensing　Germanium　Microresonator

１．研究開始当初の背景

Fast and sensitive trace gas detection is increasingly needed in many chemical and biological sensing applications ranging from environmental monitoring to industrial process control as well as medical diagnostics. One of the most promising detection techniques is laser absorption spectroscopy in mid-infrared (MIR) spectral range of 2-20 μm, since many gas molecules experience strong fundamental vibrational absorption in this domain. Traditional free-space MIR spectroscopy systems are bulky, expensive and require large sample volume. This is unacceptable in the applications such as medical diagnostics through human exhaled air analytics. Miniaturized and low-cost systems based on on-chip photonic integrated circuits are thus highly desirable.

２．研究の目的

This research thus aims to develop such an MIR photonic platform on silicon (Si) substrate, benefiting from excellent compatibility with mature CMOS manufacture process and capability of large scale integration. Specifically, optical waveguides for routing MIR light signals on-chip need to be demonstrated. Moreover, to obtain high gas detection sensitivity comparable or better than conventional large and bulk MIR spectroscopy systems, long enough effective optical absorption path length is required in limited footprint on a Si chip. This will be achieved by using microresonators (e.g., microdisks) in which light can travel inside the resonators and be absorbed multiple times. Once demonstrated, the applicability of these photonic devices to the gas sensing should also be investigated.

３．研究の方法

In order to realize these targets, material suitable for MIR photonic devices should firstly be determined. In this research, Si itself and Ge were chosen due to their excellent properties in the MIR wavelength range. The research is then performed according to the following steps in details: (1) optimization of the material performance, specifically, to reduce the MIR absorption of Ge grown on Si substrate; (2) design and fabrication of photonic devices, including waveguides and microdisk resonators, by using these materials; (3) establishment of characterization methods for these devices and performing measurement; and (4) investigation of the applicability and feasibility of designed devices to gas sensing.

４．研究成果

(1) Reduction of MIR absorption of Ge grown on Si substrate

Although crystalline Ge is expected to be a transparent material in the mid-infrared region, when epitaxially growing on Si substrate, it might become absorptive due to free-carrier absorption. These free carriers are usually generated due to the threading dislocations caused by large lattice mismatch between Si and Ge. Post-growth thermal annealing is found to be effective to reduce the threading dislocation densities in Ge, thus reducing free-carrier absorption. Fig. 1 shows the absorption coefficient of Ge-on-Si under different annealing temperatures near operating wavelength, measured by FTIR. An optimized temperature of 650 °C was found to be able to significantly reduce the absorption coefficient, down to less than 10 cm^{-1}. These substrates are thus promising platform for fabrication of MIR waveguide devices.

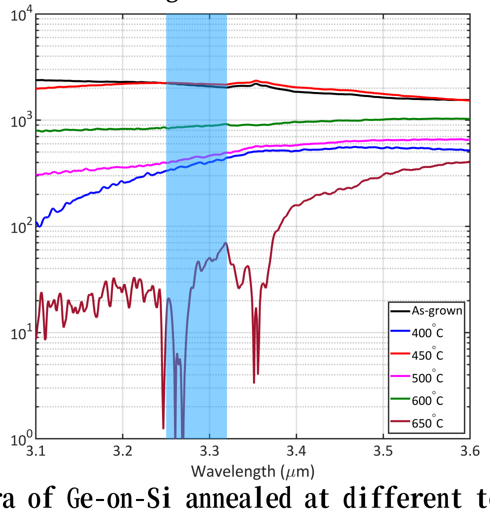

Fig. 1 Absorption spectra of Ge-on-Si annealed at different temperatures. Shaded area indicates operating wavelength of the devices.

(2) Establishment of MIR waveguide measurement system

Unlike that in communication wavelength band, the measurement of optical waveguide devices in MIR is far more difficult due to lack of available instruments in MIR, such as lasers with wide wavelength tuning range, low noise and fast detectors, optic and fiber components, and so on. A home-made MIR waveguide transmission measurement system has been established for characterization of optical waveguide devices. The laser source is a DFB intercascade laser at 3.27 μm, or a difference frequency generation laser at 3.3 μm. Both lasers can be tuned over a wavelength range of ~10 nm by a combination of current and temperature tuning, which are useful for measurement of transmission spectra of microresonators. The collimated free-space output from these lasers is modulated by an optical chopper and coupled into single-mode InF_3 fiber by using a ZnSe objective lens. Laser output from striped and cleaved fiber end is then coupled into waveguides through grating couplers and the output is fed into same type of InF_3 fiber. The output from the fiber is then collimated by a CaF_2 spherical lens, filtered by a 3.5 μm band pass filter, and focused by a Black Diamond-2 asperical lens, onto a TEC-cooled InSb photoconductive detector. The output signal of the detector is finally amplified by a lock-in amplifier synchronized with the optical chopper. These home-built system allows us to measure the output power down to nano-Watt level, which is inevitable for characterization of our waveguide devices.

(3) Demonstration of MIR Ge waveguide devices

Channel waveguides and corresponding fiber-to-waveguide grating couplers are designed and fabricated by electron beam lithography and ICP-RIE dry etching, as shown in Fig. 2(a), 2(b) and 2(c). Successful transmission of MIR laser through the waveguide is observed. The total transmission loss, including propagation loss of waveguide and coupling loss of two grating couplers, is ~30 dB. The maximum coupling efficiency for the grating coupler was ~2.6%, which is much lower than the simulation value (10.7%), which could be attributed to the fact that the laser output from the fiber was not well controlled to desired polarization, in which waveguides were designed. From these experiments, the guideline for design, fabrication and characterization of MIR waveguide devices has been successfully established.

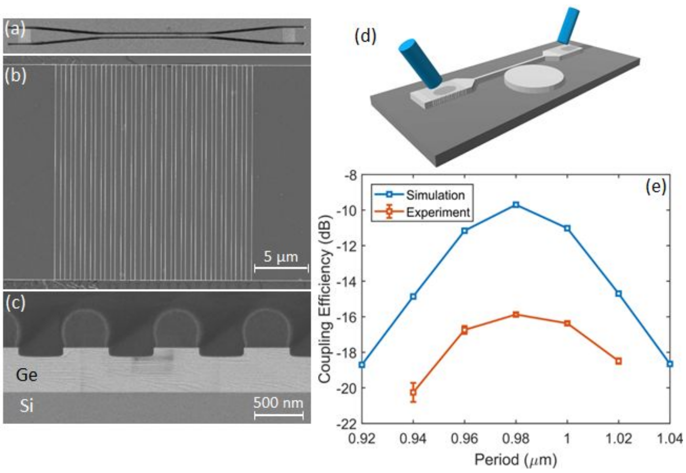

Fig. 2 (a)(b)(c)SEM images of fabricated Ge waveguide, grating coupler (top and cross-section veiws). (d) Schematic diagram of measurement scheme. (e) Comparison of simulated and experimentally measured coupling efficiency of grating couplers with different grating periods.

(4) Demonstration of MIR Si waveguide devices

To further increase the coupling efficiency as well as overlap between waveguide mode and environment, a new type free-standing waveguide structure with subwavelength grating (SWG) cladding is proposed and designed (Fig. 3(b)). Coupling efficiency of about 44% could be achieved through simulation. By using silicon-on-insulator (SOI) as test substrate, these waveguides, together with grating couplers and microdisk resonators have been fabricated, as shown in Fig. 3(a) and 3(c). Coupling efficiency of over 10% is achieved (Fig. 3(d)), which is 4 times higher than those of Ge-on-Si platform and enables us easily to perform the further spectrum measurement (Fig. 3(e)). Resonance in the microdisk resonators was not observed from the transmission spectra. Analysis indicate that this is because the coupling between the waveguide and microdisk is too weak and the problem should be solved by increasing the length of the coupling segment, and further experiment runs are planned to verify this.

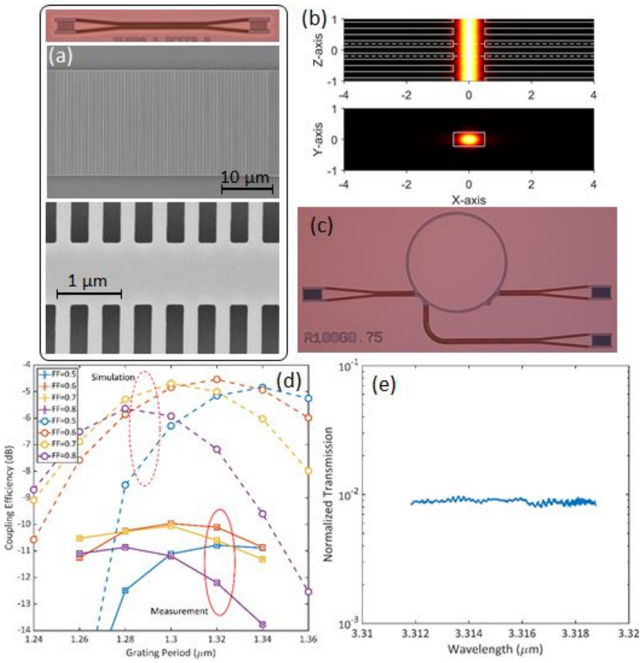

Fig. 3 (a) Microscope and SEM images of fabricated SWG-cladded waveguide and grating coupler. (b) Electromagnetic field distribution of guided mode in SWG-cladded waveguide. (c) Microscope image of fabricated microdisk resonator. (d) Comparison of simulated and experimentally measured coupling efficiency of grating couplers with different grating periods and filling factors. (e) Typical measured transmission spectrum of SWG-cladded waveguide.

(5) Analysis of detection sensitivity of microresonator-enhanced gas sensing

The sensitivity of CH_4 gas detection by using microdisk resonators has been analyzed and the results are shown in Fig. 4. The effective absorption path length (L_{eff}) could be significantly enhanced when microdisk was operating near critical coupling. The maximum L_{eff} is found to be increased as the intrinsic Q-factor of microdisk increases. For a feasible Q-factor of 1000, L_{eff} of longer than 1 meter can be readily achieved in a microdisk with radius of 100 μm, that is, with a device footprint of only 0.04 mm^2. These results indicate that the proposed platform is very promising for high sensitivity on-chip gas detection and can be manufactured with extremely small size.

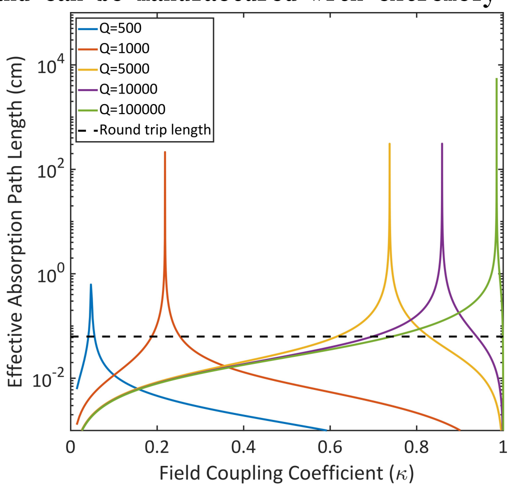

Fig. 4 Effective absorption path length of microdisk resonator with different Q-factors

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６．研究組織

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