Graphene/III-V Electro-Optic Hybrid Devices

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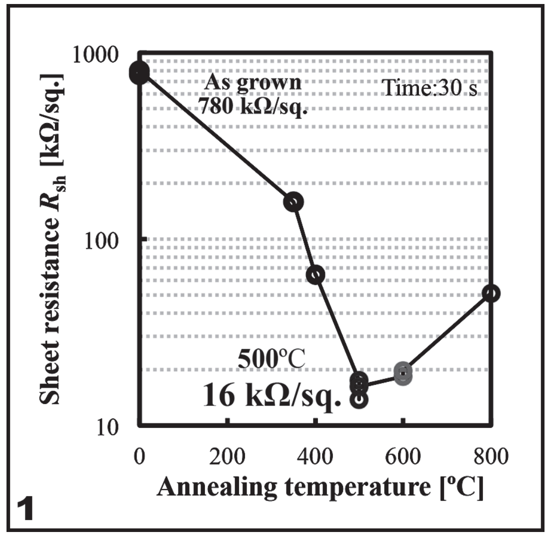
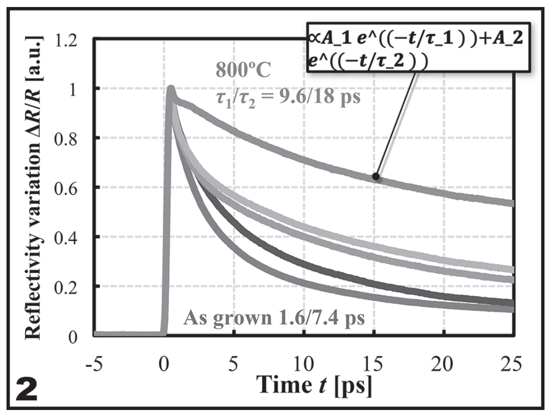
Abstract and Introduction:

Intracavity loss modulation is a promising method for broadband noise suppression in a modelocked laser. However, pure loss modulation with bandwidth beyond megahertz is rarely achieved with traditional electro-optic materials due to intrinsic resonances, amplitude and phase coupling or signal propagation delays. Graphene, arising as an unconventional two-dimensional material, exhibits an interband absorption of 2.3% from visible to infrared wavelengths, which is controllable by an external electric field [1]. This exciting property has been utilized recently and has led to unprecedented noise levels in compact fiber-based modelocked lasers [2,3]. In this work, we integrate a graphene modulator on a semiconductor-based saturable absorber mirror (SESAM), which serves as a device for initialization and stabilization of modelocking. This hybrid device exhibits modulation bandwidth beyond 5 MHz, which is sufficient for most noise-suppression applications. The realization of this hybrid device is based on the design and improvement of the top silicon-doped GaAs layer of the saturable absorber mirror, functioning as a transparent electrode. Various annealing conditions of the top layer and the resulting sheet resistance, carrier lifetime, and optical absorption changes are presented and discussed, along with the modulation performance of the graphene modulator.

Experimental:

A SESAM wafer consists of a 24-pair GaAs/AlAs distributed Bragg reflector (DBR), a low-temperature grown Er-doped InGaAs quantum well (LT-Er:InGaAs QW), a LT n-GaAs cap layer (Si: 5×10^{17} cm^{-3}). The LT-Er:InGaAs QW was used as a saturable absorber, which enables ps-order carrier relaxation times. In order to reduce the carrier relaxation time, the InGaAs QW and the following n-GaAs layer were epitaxially grown at low temperature, which led to a large number of crystal defects. Before the device fabrication the SESAM wafer was annealed at 500°C for 30 s by rapid thermal annealing (RTA) in order to lower the sheet resistance of the wafer; 20 nm Ni and 80 nm AuGe were then thermally evaporated onto the SESAM as a bottom electrode. The device was then annealed again at 350°C for 120 s by RTA to form ohmic contacts. A 50 nm Ta_2O_5 was then deposited using reactive DC sputtering; 10 nm Ti and 90 nm Au were thermally evaporated as a top electrode onto





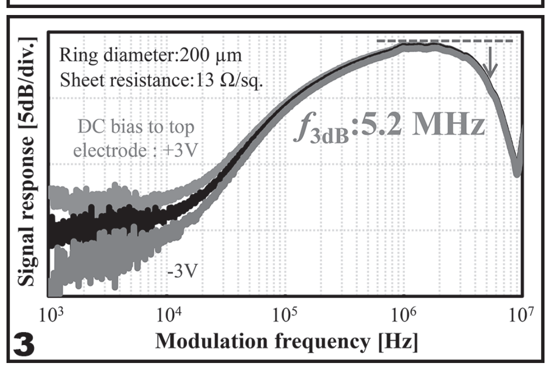


***Figure 1, top:** The sheet resistance of the annealed SESAM, measured by four-point probe method directly without metallic pads. **Figure 2, middle:** The carrier relaxation time properties of SESAMs after the annealing process. The curves represent from the bottom as grown, 400°C, 500°C, 600°C, and 800°C, respectively. **Figure 3, bottom:** The frequency response properties of the modulator.*

which CVD-grown graphene was transferred. Unused graphene was removed by oxygen plasma etching to reduce the device capacitance. After finishing the fabrication, the frequency response and the modulation depth mapping of the modulators were measured by a network analyzer and a lock-in amplifier.

Results and Discussion:

Figure 1 shows the effects of the annealing process on sheet resistance of SESAMs were examined by 4-probe method directly on SESAM, without metal contacts. At 800°C annealing temperature, silicon oxide was deposited on SESAM before annealing to prevent evaporation of As from the surface. The un-annealed sample exhibited a poor conductivity of 780 kΩ/sq., which likely resulted from crystal defects induced by the low growth temperature and charge traps from surface states of n-GaAs. When SESAM was annealed at 500°C for 30 s, the sheet resistance was improved nearly 50-fold to 16 kΩ/sq. We attribute this to the reduction of crystal defects or charge traps, while at annealing temperatures of more than 500°C dopants diffused out from the conducting layer or Ga diffused into the SiO2 layer and formed vacancies acting as trapping sites [4].

The saturable absorption of the LT-Er:InGaAs QW after the annealing process was also investigated as shown in Figure 2. It can be seen that annealing increased the slow component of the carrier relaxation; however, for annealing temperatures below 600°C, the resulting longer relaxation time should still be tolerable for sub-picosecond pulse generation.

Figure 3 shows the frequency response of this hybrid graphene/III-V modulator with the SESAM annealed at 500°C for a device with an aperture diameter of 200 µm, and a post-anneal sheet resistance of 13 kΩ/sq, measured by the circular transmission line method (c-TLM). The modulator was operated by an AC voltage of 2 V_{rms}, and illuminated by a 1550 nm continuous-wave laser diode.

The device exhibits a modulation bandwidth beyond 5 MHz thanks to the improvement of the sheet resistance. This value is sufficient for most solid-state laser applications. We assume that the DC bias dependence at low frequencies is likely explained by an equivalent circuit model considering the series capacitance that results from the Ta_2O_5 insulating layer and the depletion region formed at the surface of the n-GaAs layer. The modulation depth mapping in Figure 4 shows uniform modulation area within the active aperture.

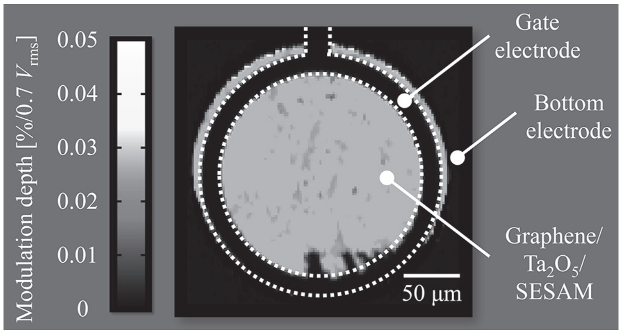


Figure 4: Modulation depth mapping of the modulator. The ring diameter is 200 µm.

Conclusions and Future Work:

We demonstrated an electro-optic graphene/III-V hybrid modulator achieving an operation bandwidth beyond 5 MHz. A post-growth annealing processes successfully reduced sheet resistance of the SESAM from 780 kΩ/sq. to 16 kΩ/sq., which largely improved the cut-off frequency of the modulator. In the future, we are going to combine the modulator with modelocked lasers for noise suppression applications.

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