Fabrication of RF device using Intercalated Multilayer Graphene / Nickel Layered Conductor

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With the recent advances in IoT, more RF devices such as antennas and inductors are required. However, the miniaturization of RF devices using conventional metals like copper (Cu) is reaching its limits because the required length and area are determined by magnetic inductance. Unlike conventional metals, graphene has a large kinetic inductance due to its unique carrier transport with long mean free path. Therefore, graphene is expected to be effective in down scaling of RF devices. [1] Previously, we reported that a conductor structure of intercalated multilayer graphene (I-MLG) stacked on a magnetic nickel (Ni) layer reduces the patch antenna area by 66%. [2] In this study, an open stub was fabricated using highly crystalline MLG-CVD and stable $MoCl_5$ intercalation to investigate the potential of size scaling.

Fig. 1 shows a cross-section of the I-MLG / Ni layered structure. Ni layer works as a catalyst for MLG CVD and it also acts as a "magnetic core" since the current is expected to flow the surface through I-MLG layer due to the skin effect at high frequency.

Patterns fabricated with Cu, Ni and I-MLG/Ni are shown in Fig. 2. The quarts glass substrate (1.0 cm × 1.0 cm) surfaces were first cleaned by organic cleaning and then nickel (Ni) film with a thickness of 1μm was deposited by the DC magnetron sputtering. Then, the Ni was patterned by photolithography and wet etching to fabricate the pattern as shown in Fig. 3. MLG-CVD was then performed at 900°C to form MLG films with good film quality using a split precursor supply method developed to improve crystallinity and uniformity, as shown in Fig. 4. [3] Then, $MoCl_5$ intercalation doping was performed at 300°C. Fig. 5 shows a comparison of the G-band shifts in the Raman spectra after intercalation. The shift of the G-band to higher wavenumbers indicates doping. Finally, the pattern was connected to the measurement substrate and connected to a network analyser as shown in Fig. 6.

Fig. 7 shows the transmission characteristics measured with the network analyzer for the Cu, Ni, and I-MLG / Ni stubs. The stub is an open-ended transmission line that is connected in parallel to the main line. In Cu, a peak was obtained at 3.6 GHz. In Ni, the peak was shifted to 3.2 GHz due to the high magnetic permeability. In I-MLG/Ni, a peak was obtained at 3.5 GHz. In an open stub, the length of the line is expressed as 1/4 of the wavelength, at which the peak occurs. The frequency is inversely proportional to inductance and capacitance. Since the capacitance is considered to be the same, this peak shift is considered due to the increased inductance due to the I-MLG / Ni structure. The shift was less than that of Ni, however, the loss seems to be less than that of Ni probably due to the lower resistance than Ni. Table 1 shows the resistance measured with four-terminal method for the Cu, I-MLG / Ni, and Ni. I-MLG / Ni had a higher resistance than Cu, and it is most likely caused the peak intensity of I-MLG / Ni to be 8.7 dB smaller than that of Cu.

In this study, we investigated the possibility of I-MLG / Ni structure by a MLG CVD process and doping of $MoCl_5$ intercalation for RF devices. This structure resulted in a resonance frequency shift indicating the possibility of size reduction, although the effect is less than expected from the previous antenna probably due to the lower frequency and thinner I-MLG thickness. Further improvements will be expected at higher frequencies due to thinner skin depth and with thicker I-MLG which is expected to increase the current through I-MLG layer. The developed structure is expected to be applied to the miniaturization of RF devices beyond the limits of conventional metals with further improvements.

References

1. J. Kang, Y. Matsumoto, X. Li, J. Jiang, X. Xie, K. Kawamoto, M. Kenmoku, J. H. Chu, W. Liu, J. Mao, K. Ueno, and K. Banerjee, Nature Electronics, **1**, 46-51(2018).
2. K. Ueno, K. Masukawa and S Tanaka, Ext. Abst. 2024 Int. Conf. Solid State Dev. Mat. (SSDM), pp.143-144.
3. K. Masukawa, K. Ueno, Abst. Adv. Met. Conf. (ADMETA Plus 2023), 7-3.

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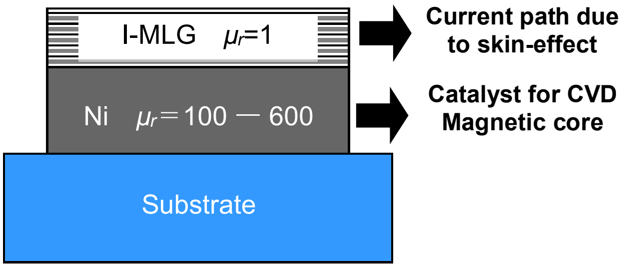

Fig. 1. Cross-section of the I-MLG /Ni layered structure. Higher inductance density is expected with kinetic inductance of I-MLG and magnetic Ni layer.

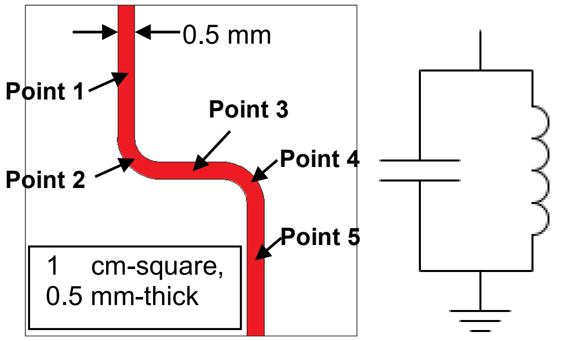

Fig. 2. Stub pattern designed and fabricated and equivalent circuit at a resonance frequency

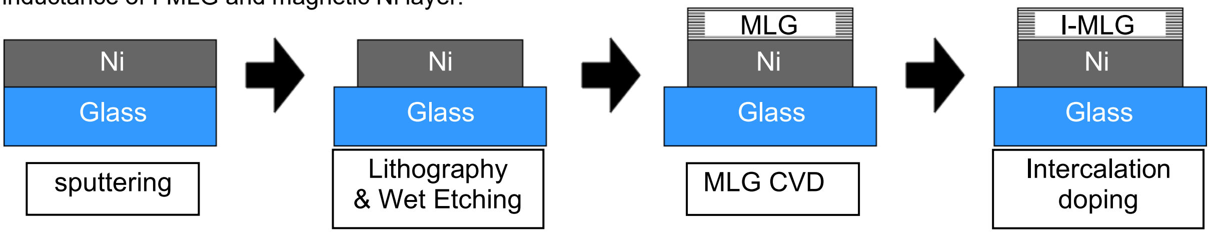

Fig. 3. Fabrication process flow of I-MLG / Ni layered structure. Highly crystalline MLG can be deposited on Ni.

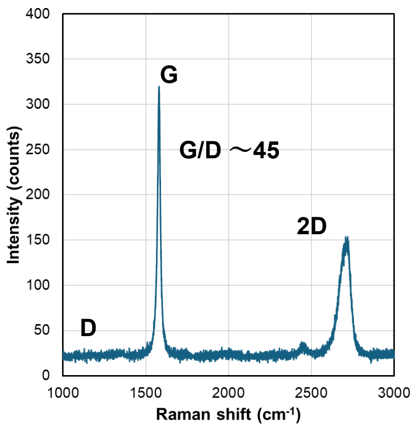

Fig. 4. Raman spectrum after CVD. Highly crystalline MLG was deposited.

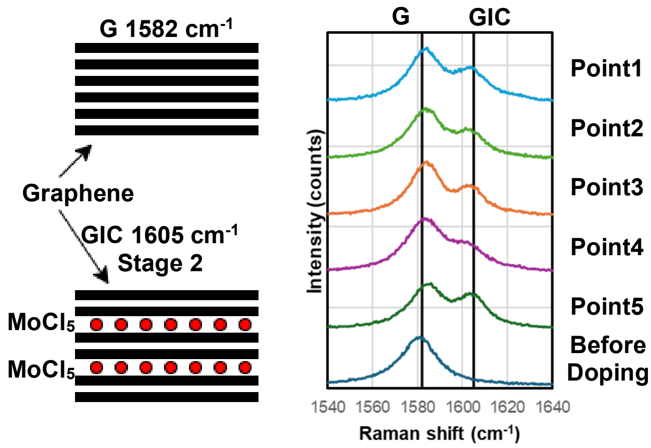

Fig. 5. Raman spectra after intercalation doping. Uniform doping was achieved on the entire pattern.

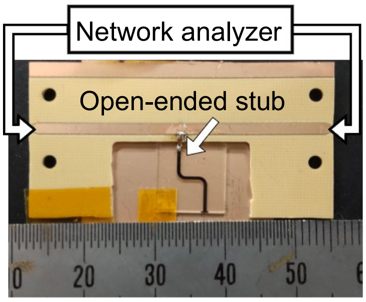

Fig. 6 Photo of fabricated I-MLG / Ni stub connected to measurement substrate.

Table 1. Comparison of sheet resistance between Cu, I-MLG/Ni, and Ni.

Conductor	Sheet resistance (Ω/sq)
Cu	0.021
I-MLG/Ni	0.111
Ni	0.309

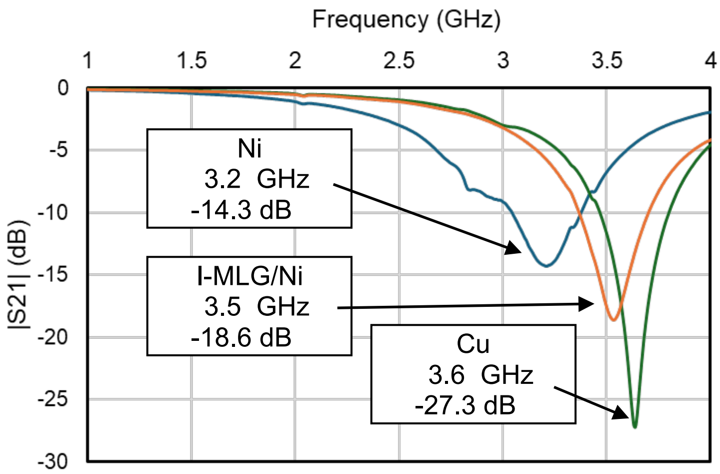

Fig. 7. Transmission coefficient of fabricated Cu, I-MLG / Ni, and Ni open stub. Peak shift of I-MLG / Ni was less than that of Ni, however, the loss seems to be less than that of Ni.