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Generation of Local Magnetic Field by Nano Electro-Magnets

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1. Introduction

The generation of local magnetic field is an important ingredient of newly developed solid-state devices where the local control of electron or nuclear spin is required. One example could be a quantum-computing device that consists of magnetic quantum dots or molecules [1]. Recently, an electro-magnet with the diameter of several tens of μm has been fabricated and been used to manipulate magnetic particles [2]. In this work, we reduce the size of the electro-magnet into nano-meter regime and present various working examples (characterization results).

2. Fabrication and Characterization of Nano Electro-Magnets

Fabrication of Coupled Electro-Magnets

Figure 1 shows the SEM photograph of a typical coupled electro-magnet. Two concentric metal rings with separate contacts were fabricated on Si/SiO_2 substrate by a standard electron beam lithography and lift-off process. The diameter of the inner ring is 800 nm and the minimum spacing between the metal lines is slightly less than 100 nm.

Characterization of Coupled Electro-Magnets

The induced current of the inner ring was measured using lock-in amplifier, when an AC current flowed through the outer ring (Fig. 2). Figure 3 shows the amplifier output of the imaginary (Y) part of the induced current in the lower loop, as a function of the rms voltage applied on the upper loop (V_{in}). It increases almost linearly with V_{in}. Figure 4 shows Y as a function of the frequency (f). The value of Y also increases up to approximately 1 kHz. The induced current is approximately given by $-(V_{in}/R^2)j\omega M$ where R is the resistance of the ring, $\omega = 2\pi f$, and M is the mutual inductance. The increase of the induced current observed in Fig. 3 and Fig. 4 originates from the successful Faraday coupling between two rings. The decrease in the range f > 1 kHz is due to the low pass characteristic of the lock-in amplifier. The value of the mutual inductance (M) estimated from the measured results is several orders of magnitude larger than the usual value calculated from small coupled-rings shown in Fig. 1. Such a large value is the result of singularity existing in the overall current loops. The actual measurement circuit consists of two macroscopic closed current loops that are in close contact with each other only at the position where the nano pattern of Fig. 1 exists. Figure 5 shows the numerical simulation results of the mutual inductance between two loops with the diameter of 1 m and the separation of d. The value of M exhibits a diverging behavior as d approaches a small value.

Capture of magnetic particles

A drop of solution containing iron oxide particles was applied on the rings when a DC current was applied. Soft blow dry was performed when the current is on, then the substrate was carefully examined by SEM. The magnetic field in the inner part of the ring is expected to be a maximum and is expected to capture the magnetic particles. Several rings were tested at various current levels. There are clear black marks at the inner part of the ring only when the current level > 100 μA. Figure 6 (a) shows such an example (Fig. 6 (b) is a magnified photo of Fig. 6 (a)). Since the width of the ring is narrow, the maximum current is limited only at several hundred μA. Therefore, the magnetic field inside the ring is barely enough to hold the magnetic particles and they can easily fly away by the blow dry, only leaving the observed marks.

3. Conclusions

We present two types of experiments demonstrating the local generation of magnetic field by nano electro-magnets. Induction of the current through the metal ring by the time-varying magnetic field in another nearby ring has been demonstrated. The amount of the induced current is unexpectedly large and can be explained by the singularity of the measurement circuit. Such singularity is only possible by successfully connecting nano-meter sized rings to the macroscopic loops. Secondly, DC current in the small metal ring is shown to capture the magnetic particles.

Acknowledgements

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References

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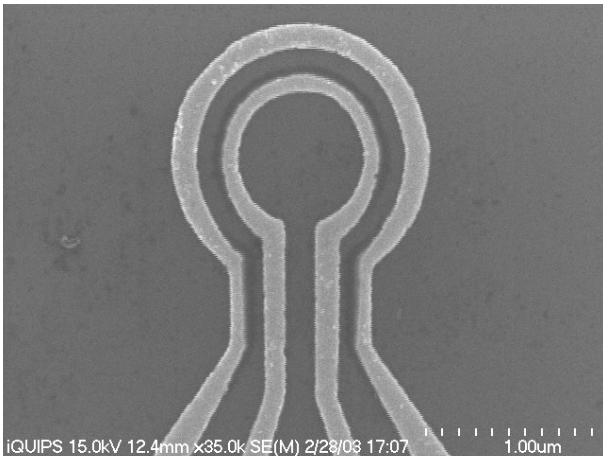

Fig. 1 The SEM photo of a typical coupled electro-magnet rings.

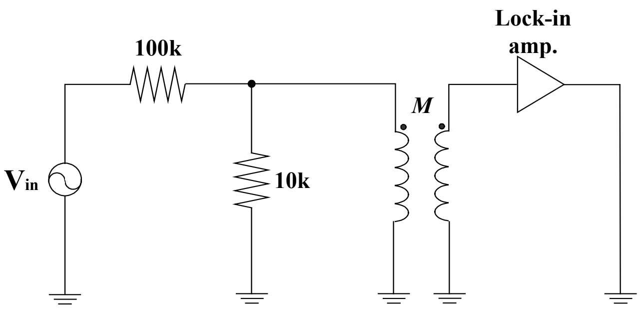

Fig. 2 A schematic of the measurement circuit.

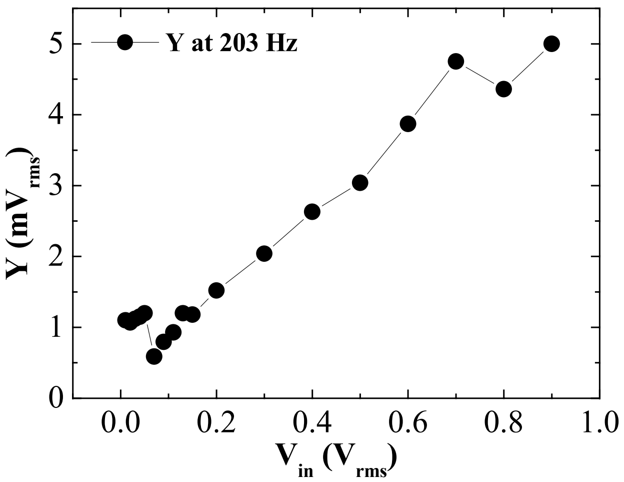

Fig. 3 The imaginary part of the induced current (Y) as a function of the rms input voltage (V_{in})

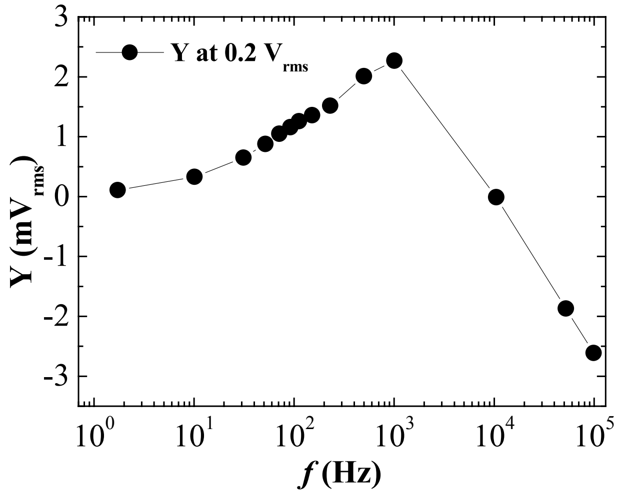

Fig. 4 The value of Y as a function of f

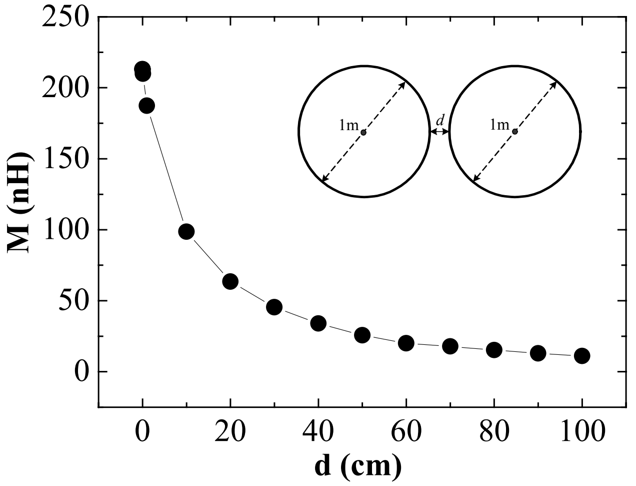

Fig. 5 The simulated mutual inductance as a function of d (for the circuit shown in the inset).

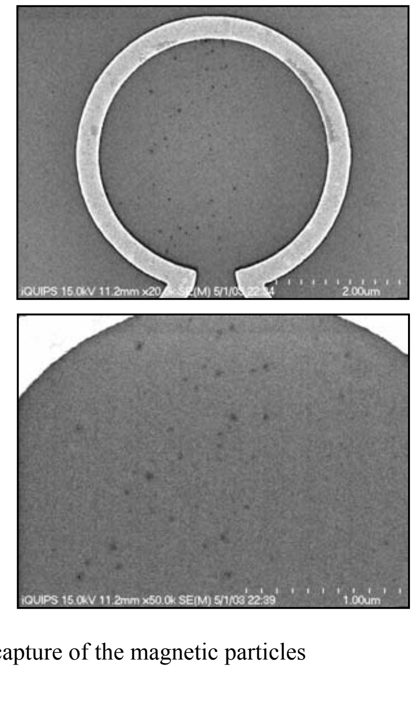

Fig. 6 The capture of the magnetic particles