Using standard nuclear magnetic resonance (NMR) technique and a well-fabricated sample, we have succeeded in directly observing local magnetic field generated by a micro-magnet Ni$_{45}$Fe$_{55}$ (the thickness of 400-nm) which was sputtered on an Al layer of 20-nm thickness. Improved sensitivity of our NMR technique enabled us to clearly observe Al-NMR signals, which are confirmed to come from Al nuclei in the 20-nm layers. From the analysis of the Al-NMR spectra, the local magnetic field was found to be $+0.17 \pm 0.02 (-0.20 \pm 0.01)$ Tesla, the sign of which is consistent with the geometry that the external magnetic field was applied perpendicular (parallel) to the Al layer.

The present study gives a potential key element toward realizing higher resolution in magnetic resonance imaging (MRI).

Based on the rapid progress of pulse techniques in NMR, magnetic resonance imaging (MRI) was invented and has been a well-known and well-established powerful method to obtain nondestructively three-dimensional (3D) images of human cells and organs. To obtain 3D image data, MRI requires a gradient in the static magnetic field. Since NMR frequency is exactly proportional to the magnetic field applied, the gradient results in spread of frequencies. Thus, the spatial resolution of MRI depends on not the magnitude but the gradient of the magnetic field. So far, the resolution of MRI systems for medical use is of the order of millimeters or micrometers. To obtain higher resolution, the sample should be smaller, and hence, the smaller amount of nuclei. This results in reducing signal to noise ratio (SNR), because NMR detects the nuclear-spin signals through coils (“inductive detection”) placed around the material of concern. Contrary to these technical difficulties in MRI, it has become possible to detect a single electron spin in magnetic resonance force microscopy (MRFM) because NMR detects the nuclear-spin signals through coils (“inductive detection”) placed around the material of concern. NMR has been well-established. Thus, a breakthrough can be expected if the spatial resolution in inductive NMR is developed based on high-sensitivity technique. As can easily be seen from the principle of resonance, the greater the gradient in the magnetic field, the higher the resolution. One of the most practical ways to produce a greater gradient than that in standard MRI would be to place a micro-scale ferromagnet close to a thin layer of nuclei of concern.

In this Letter, we show that, employing inductive NMR method, we have succeeded in the detection of signals coming from the nuclei that feel the local magnetic field generated by a micro-scale ferromagnet. A well-fabricated sample and improved sensitivity of our NMR system enabled us to probe Al-NMR signals coming from a 20-nm Al layer above which a Ni$_{45}$Fe$_{55}$ alloy of 400-nm thickness was sputtered. From the difference in the Al-NMR spectra under different orientations of the magnetic field, we confirmed that the Al signals surely stem from the Al-layer of 20-nm thickness that feels the local magnetic field. We also discuss the gradient of the local magnetic field from the simulation of the Al-NMR spectra.

Figure 1(a) shows a schematic view of our sample used in this study. The Ni$_{45}$Fe$_{55}$ of 400-nm thickness produces local magnetic field, $B_{\text{local}}$, in the Al-layer of 20-nm thickness just below. From a de SQUID measurement, the magnetization of the sample was found to saturate when an external magnetic field $B_{\text{ext}}$ over 3 Tesla was applied. As can be seen from Fig. 2 (a) and (b), the Ni$_{45}$Fe$_{55}$ produces positive (negative) $B_{\text{local}}$ at the Al layer when the $B_{\text{ext}}$ is parallel to the $z$ ($y$) axis. As a reference for the Al-NMR spectra, we placed an Al metal [Al(ref)] in the NMR coil along with the sample. The coil was made of pure-Ag metal, which helped us not to observe the signal from the coil. We irradiated the sample with RF pulses of a given frequency, $f_{\text{RF}}$, that the signal generator produces. As a response from the nuclei, we recorded the spin-echo intensity with sweeping the $B_{\text{ext}}$. All the Al-NMR spectra were obtained for the $B_{\text{ext}}$ over 3 Tesla to maximize the $B_{\text{local}}$. To detect the nuclear-spin signals in the 20-nm layer, we did the followings. First, we wound the coil directly on an insulating thin tape that wraps both the sample [10-mm width, 20-mm distance,
0.5-mm thickness (see Fig. 1(a)) \times 3 pieces] and the Al(ref) [4-mm width, 12-mm distance, 10-\mu m thickness \times 1 piece]. Second, using a network analyzer, we realized an ideal impedance matching of the resonance circuit; the Smith Chart showed that the imaginary part was 0 \pm 1 ohm and the real part 50 \pm 10 dB at around the $f_{op}$. Third, using a standard $^4$He-flow cryostat (Cryoindustry Co. Ltd), we cooled the sample down to 1.7 K. In reducing the $^4$He-gas pressure, we confirmed that the RF pulses did not result in arching. Fourth, in observing the spin-echo signal, we employed the quadrature detection to increase SNR, and phase-cycling techniques to cancel ring down noises caused by the coil.

We first obtained the NMR spectra with $B_{ext}||z$ [Fig. 2(a)]. Figure 3(a) and (b) show the spectra obtained by sweeping the $B_{ext}$ at a given $f_{op}$. For simplicity and convenience, the $B_{ext}$ is shifted as $\frac{f_{op}}{\gamma} - B_{ext}$, where $^{27}\gamma$ (=11.094 MHz/T) is the gyromagnetic ratio of $^{27}$Al. A sharp peak observed nearly at the origin is assigned to $^{63}$Cu. This is validated by an experiment in which the Al(ref) was extracted from the coil. Here, we label the other signals as I, II, III and IV. In the followings, we clarify that Signal IV comes from the 20-nm Al layer that feels the $B_{local}$, and that the others from materials outside the NMR coil.

First we show that Signal I and Signal II are assigned to $^{65}$Cu and $^{63}$Cu, respectively. Clearly seen for Signal I, the smaller the $f_{op}$, the smaller the $B_{peak}$, where $B_{peak}$ is the peak position of the signal. It was found that $f_{op} = g B_{peak}$, where $g$ (=12.089 MHz/T) is the gyromagnetic ratio of $^{65}$Cu. Thus, we can safely assign Signal I to $^{65}$Cu. In the same way, Signal II is assigned to $^{63}$Cu. This is validated by the fact that the intensity ratio of Signal I over Signal II is nearly equal to the natural abundance ratio of Cu isotopes, i.e., $^{65}$Cu : $^{63}$Cu = 30.9 \% : 69.1 \%. Here, it is quite natural to raise a question why Cu signals can be observed when the sample does not contain Cu nuclei and the coil is made of purely Ag. To clarify this, we performed measurements under the same conditions except that the sample was extracted from the coil. In the experiments, signals were observed at the peak positions of Signals I and II. This indicates that these signals come from nuclei outside the coil. We speculate that they originate from a Cu tube which shields electromagnetic noises from outside, or a capacitor made of Cu metal. In general, this is not unusual but sometimes happens in high-sensitivity NMR measurements. In other words, the fact that we detected these signals proves the high sensitivity of the present measurements. In additional to Signals I and II, Signal III was observed in the experiment without the sample. Since the $B_{peak}$ is close to the Al(ref), we speculate that Signal III is ascribed to Al-NMR signal from Al$_2$O$_3$, the constituent of macor which our NMR probe contains.

Now we clarify that Signal IV comes from the Al nuclei in the 20-nm layer. For the spectra at smaller $f_{op}$ (=52.417 MHz, 41.719 MHz), the peak position of Signal IV is unambiguously defined, since the signals are clearly separated from Signal II. On the other hand, this is not the case for the spectra at larger $f_{op}$ (=94.127 MHz, 81.585 MHz), because Signal IV is superimposed on Signal II. Thus, we defined the peak position of Signal IV by the kink which can be more clearly seen in the expanded views [Fig. 3(b)]. In Fig. 3(d), we plot the peak positions of Al(ref), Signals I, II and IV in the form of $f_{op}$ versus $\frac{f_{op}}{\gamma} - B_{ext}$. Except for Signal IV, due to the resonance condition that $f_{op} = g B_{ext}$, the fitted lines cross the origin and the slopes give the value of $g = 1.0 \pm 0.02$ Tesla. It is to be noted that for the Al signals that feel the $B_{local}$, the values of $\frac{f_{op}}{\gamma} - B_{peak}$ (= $B_{local}$) should be non-zero and constant regardless of the $f_{op}$ values, as easily seen from $f_{op} = g(B_{peak} + B_{local})$. Thus, it is very likely to say that Signal IV should come from the 20-nm Al layer that feels $B_{local} = +0.17 \pm 0.02$ Tesla.

To confirm this, we utilized the fact that the Al-layer should feel negative $B_{local}$ if the $B_{ext}$ is applied in the $+y$ direction [Fig. 2(b)]. In this case, the peak position of Signal IV should be opposite in reference to the peak of the Al(ref). This is exactly what Fig. 3(c) shows, as
expected. We would like to stress that, as is illustrated in Fig. 3(d), the values of $\frac{f_{\text{op}}}{2\gamma} - B_{\text{peak}}$ are shifted by $-0.20 \pm 0.01$ Tesla irrespective of the $f_{\text{op}}$. Thus, the line shape of Signal IV can be well-reproduced when a field gradient of $\sim 0.38$ T/µm is assumed.

In conclusion, using inductive NMR method, we have succeeded in directly observing the local magnetic field $B_{\text{local}}$ generated by the Ni$_{45}$Fe$_{55}$ micro-magnet. The success is based on our sensitivity sufficiently high to detect nuclear-spin signals from the 20-nm layer as well as on the well-fabricated sample. From the analysis of the spectra, we found that the $B_{\text{local}}$ was $+0.17 \pm 0.02$ Tesla ($-0.20 \pm 0.01$ Tesla) when the $B_{\text{ext}}$ was applied perpendicular (parallel) to the Al layer. Our preliminary simulation showed that the spectra can be well-reproduced with a field gradient of $\sim 0.38$ T/µm, which needs to be tested in our future experiments. Since the sample we used is planar-shaped in which a magnetic thin film is deposited, the present result gives a potential key element toward realizing high-resolution MRI.

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