Distribution of parallel vortices studied by spin-polarized neutron reflectivity and magnetization

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We present the studies of non-uniformly distributed vortices in Nb/Al multilayers at applied field near parallel to film surface by using spin-polarized neutron reflectivity (SPNR) and DC magnetization measurements. We have observed peaks above the lower critical field, H_{c1}, in the *M-H* curves from the multilayers. Previous works with a model calculation of minimizing Gibbs free energy have suggested that the peaks could be ascribed to vortex line transitions for spatial commensuration in a thin film superconductor. In order to directly determine the distribution of vortices, we performed SPNR measurements on the multilayer and found that the distribution and density of vortices are different at ascending and descending fields. At ascending 2000 Oe which is just below the first peak in the *M-H* curve, SPNR shows that vortices are mostly localized near a middle line of the film meanwhile the vortices are distributed in broader region at the descending 2000 Oe. That is related to the observation of more vortices trapped at the descending field.

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As the applied field is sightly tilted ($< 3.5^o$), we observe another peak at a smaller field. The peak position is consistent with the parallel lower critical field ($H_{c1\parallel}$). We discuss that the vortices run along the applied field below $H_{c1\parallel}$ and rotate parallel to the surface at $H_{c1\parallel}$.

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I. INTRODUCTION

Vortices running parallel to surface in a thin superconducting film have been widely investigated theoretically and experimentally. As the field applied parallel to surface, the Bean-Livingston surface barriers significantly contribute to ingress and egress of vortices [1,2]. They also could do an important role in determining density and distribution of vortices, as the film thickness is comparable to the London penetration depth [3,4]. Unusual prominences in a M-H curve above H_{c1} have been observed from superconducting films by using several different techniques, including electron tunneling [5], microwave absorption [6], resistivity [7], superconducting channel device [8], SQUID magnetization [3,9], torque magnetization [4], and vibrating reed [10,11]. Guimpel et $al.$ [3] has suggested that the peak could be due to the vortex line transitions for spatial rearrangements with a model calculation of minimizing Gibbs free energy. The idea of minimizing free energy with vortices has been further developed by Brongersma et $al.$ with Monte Carlo simulation [4]. However the above techniques measure only the average magnetization or the result of vortex motions. It means that they can not determine the location of vortices with the mesurements alone. Furthermore experimental measurements from a thin $YBa_2Cu_3O_{7-x}$ film [10] disgree with the model calculation of the free energy with vortices [11]. Therefore only a direct measurement on the location of vortices would clarify whether the peaks comes from the vortex line transitions.

Since spin-polarized neutron reflectivity (SPNR) could detects spatial gradient of magnetic field, it has been used to determine London penetration depth of high-Tc superconductors as well as conventional superconductors [12] at a small field. In the regime of saturated field, SPNR has showed a capability to observe vortices [13,14]. A theoretical model calculation by Han et $al.$ [13] has demonstrated that it could be able to measure the density and also the distribution of vortices. By using another advantage of SPNR that measures only parallel component of magnetization due to a scattering selection rule, Han et $al.$ [15] has demonstrated that vortices placed perpendicular to surface considerably contribute to the

magnetization measurements even at a small tilted field.

In this paper, we introduce SPNR and magnetization measurements from the vortices in Nb/Al mulitilayers in Sec. II and present the results in Sec. III. A model calculation for minimizing Gibbs free energy is discussed in Sec. IV and the magnetization measurements under tilted fields are presented in Sec. V. In the last section, we summarize the main conculsions.

II. EXPERIMENTAL DETAILS

Nb(72Å)/Al(20Å), Nb(100Å)/Al(20Å) and Nb(130Å)/Al(20Å) mulilayers with repeating 20 times respectively were deposited on Si substrates by direc-current sputtering under a base pressure of $\sim 10^{-4}$mTorr and the Ar partial pressure of 5mTorr. During the deposition, the power was applied to a Nb target with 275 watts (297 voltages) and a Al target with 200 watts (372 voltages) at which the deposition rate was 5.9 Å/sec for Nb film and 4.7 Å/sec for Al film meanwhile the substrate was placed at the ambient temperature. Tc of the Nb(72Å)/Al(20Å) multilayer, 7.25 ± 0.25 K, was determined by magnetization measurement at applied field 50 Oe.

For magnetization measurements, a multilayer mounted on an extended sample holder was placed in a cryostat with the geometry where the film surface runs near perpendicular to a pick-up coil of the SQUID and zero-field cooled. Subsequently the field was applied. The tilt angle between the surface and applied field was controlled by shimming non-magnetic plastic pieces between the sample holder and sample. The tilt angle was reproducible within uncertainty, $\pm 0.25^{o}$.

SPNR measurements from the Nb(72Å)/Al(20Å) multilayer were performed at POSY1 reflectometer, Intense Pulsed Neutron Source, Argonne National Laboratory. The polarization efficiency $\sim 97\%$ and the instrumental resolution $\Delta q/q = 0.053$ were counted to analyzing the reflectivity data. The specimen was zero-field cooled and the field was applied parallel to the film surface at tilt angle $< 0.5^{o}$. The polarized neutrons was reflected from

the multilayer with incident angle 0.45^o.

III. DATA ANALYSIS AND RESULTS

Magnetizations from the multilayers were measured for ascending field at 2 K, as shown in Fig. 1. We observe the peaks (indicated by small arrows) from the multilayers. The peak positions are dependent on the configuration of the films. The peak from the Nb(72Å)/Al(20Å) multilayer is more notable than the others. The detail magnetization studies will be discussed in Sec. V. For more understanding of the interfaces of the Nb(72Å)/Al(20Å) multilayer, specular x-ray reflectivity measurement was carried under atmosphere. Figure 2 shows the grazing angle x-ray reflectivity as a function of momentum transfer, q. A best fit (solid line) shows Nb(120±20Å)/[Al(19±1.5Å)/Nb(74.5±2.5Å)]×20/Si and an extra layer at the air/Nb interface with thickness ∼60 Å and the x-ray scattering density half of Nb improves a best fit. A rms roughness at the air/Nb interface is ∼15 Å while the roughness of the Si substrate is ∼2.2 Å. Each Nb layer has the roughness ∼6 Å and each Al layer has ∼2.5 Å rough surface.

SPNR measurements were performed on the Nb[72Å]/Al[20Å] multilayer to directly determine the density and distribution of vortices which run parallel to the surface. Figure 3 (a) shows neutron specular reflectivities measured as a function of q for spin up and spin down neutrons at 700 Oe and 2 K. The oscillation period is corresponded to the total film thickness ∼2020 Å. A best fit (solid line) shows that the top Nb layer thickness is 180 ± 40 Å and multilayer [Al(20 ± 2Å)/Nb(72 ± 5Å)] × 20. However it could not reveal the buried interfaces as well as the x-ray reflectivity does because the neutron data were taken in a small-q region. The neutron reflectivity is basically consistent with the x-ray reflectivity within uncertainty and the configuration of the multilayer determined by neutron reflectivity measurement was used for analyzing the SPNR data. Figure 3 (b) shows reflectivity difference between spin-up and spin-down devided by their average ($\Delta R/\overline{R}$) that more clearly demonstrates magnetization contribution to SPNR. The solid line is a best fit without in-

cluding vortices. It showes that the London penetration depth (λ_L) of the multilayer is 1800 $\pm$ 200 Å. At a high field, vortices will enter the superconductor and SPNR would see the vortices.

Figure 4 show $\Delta R/\overline{R}$ under 2 K at ascending field 1500 Oe (a) which is just above H_{c1} and 2000 Oe (b) which is just below the first peak, as shown in Fig. 1. Below critical angle ($q \simeq$ 0.013 $\mathring{A}^{-1}$), the beam is totally reflected by the surface and the magnetization contribution to SPNR vanishes. For $q > 0.018$ $\mathring{A}^{-1}$, the reflectivity differences among the models are relatively smaller meanwhile the uncertainty is growing up. Thus, data in q-range of 0.013 - 0.0175 $\mathring{A}^{-1}$ only were fit to a theoretical model [13]. In the fit, only single parameter, density of vortices, was varying and the distribution is assumed to be mostly localized in 1 row (dashed line), 2 rows (solid line) and uniformly distributed through the whole specimen (dotted line).

The results of least χ squares fits with counting the statistical uncertainty are summarized in table I for 1500 Oe. It shows that 1 row of vortex model is slightly better than the others and the vortex density is 30 $\pm$ 6 μm^{-2} which is corresponding to the distance of vortex-vortex $\sim$1650 Å. Table II shows the χ^2 of fits for different models for 2000 Oe. The models of 1 row and 2 rows are not distinguishable with basing on the least χ^2. However the magnetic field due to the vortices in a line interferes with the surface screening fields in $\Delta R/\overline{R}$. The interference effect is more clearly seen near the first peak of $\Delta R/\overline{R}$, $q \simeq$ 0.0145 Å^{-1} in this system. It suggests that the model of 1 row is better than 2 rows. From the fit with 1 row (dashed line) the vortex density is found to be 45 $\pm$ 6 μm^{-2} that is corresponding to $\sim$1100 Å of the average distance between two adjacent vortices.

After cycling the field to 5400 Oe, SPNR measurement was also conducted from the multilayer at 2000 Oe, as shown in Fig. 5. The lines present a best fit with assuming different distributions of vortices. A goodness fit of solid line strongly suggests that the vortices stay in 2 rows, 1/3 and 2/3 of the total film thickness and the density of vortices 56 $\pm$ 2 μm^{-2} The results of fits are summarized in table III. The fits show that 2 rows of vortex model is about twice better fit than 1 row and uniform distribution. From the best

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fit with 2 rows, the nearest vortex distance is calculated to be $\sim$1110 Å with assuming a triangular vortex lattice. (b) shows the neutron scattering density profile of magnetic as well as nuclear potential that is corresponding to the fit with 2 rows in (a). The inset shows a vertical expansion.

The best fits of the SPNR data are summarized in table IV. The analyses show that vortices stay in a single row at ascending fields, 1500 and 2000 Oe, however they would like to spread into 2 rows at the cycled field 2000 Oe. More broadening at the cycled field could be explained in terms of the trapped vortices by the surfaces. The parallel magnetization (M$\parallel$) is calculated by using the density and distribution of vortices determined by SPNR with a theoretical model [15]. The M$\parallel$ shows that is unable to distinguish the differences among the fields due to large uncertainty. However they are certainly negative values even at the cycled field. We could directly compare those to the SQUID data. As shown in the table, the magnetizations of M$\parallel$ for ascending field are comparable to $\bar{M}$ directly converted from SQUID data within uncertainty however there is a big difference at the cycled field. It suggests that $\bar{M}$ of the cycled field is contributed by not only M$\parallel$ but also vortices running perpendicular to the surface. That mechanism in which vortices enter the superconducting film parallel to the surface for ascending field and rotated out of plane during reducing the field has been observed in a Nb superconducting film [15].

Although we could obtain reasonable results with the model, 1 row or 2 rows, of the vortex distributions, a Gaussian distribution could be an alternative choice for the vortices in a superconducting film. Figure 6 shows the best fits with a Gaussian distribution of vortices and table VI summarizes the results of the fits. The model of Gaussian distribution absolutely improves the fits, particularly 1500 and ascending 2000 Oe. At 1500 and ascending 2000 Oe, the full width at half maximum (FWHM) is basically the same however it shows broader at the cycled 2000 Oe. The density and M$\parallel$ are very comparable to the model of 1 row or 2 rows. Because of a limit of the SPNR sensitivity to this system, it is not able to distinguish between a Gaussian distribution and 1 row or 2 rows. However it is clear that

the vortices have a same distribution at ascending fields and they are differently distributed at the cycled field.

IV. MODEL CALCULATION AND DISCUSSION

For more theoretical understanding of vortex distribution in a superconducting film, we have developed a model calculation for minimizing Gibbs free energy. As N number of vortices enter in a superconducting film, the total free energy of the superconductor could be calculated by using a London approximation [2] with simply assuming that it is an isotropic superconducting film and impurity in the film is negligible.

$$G = G_0 + \frac{1}{2\mu_o} \int_{V_S} dv \left\{ \vec{\Phi} \cdot (2\vec{B}_L + \vec{B}_V) \right\} \tag{1}$$

where G_0 is free energy for the system without vortices, μ_o is permeability in vacuum, V_S is volume of superconductor, $\vec{\Phi}$ is vorticities, $\vec{B}_L$ is surface screening field and $\vec{B}_V$ is magnetic field due to vortices including their images. The vorticities are defined to be,

$$\vec{\Phi} = \Phi_o \sum_{k=0}^{k=N} \delta(\vec{r} - \vec{r}_k)\hat{x} \tag{2}$$

where Φ_o is a vortex flux quantum, $2.067 \times 10^9 \, \mathrm{G\mathring{A}^2}$, $\vec{r}_k$ is location of kth vortex and vortices are oriented in x-axis. As assumed that the applied field is exponentially decayed from the surface, the surface screening field is

$$\vec{B}_L = \mu_o H \left\{ \frac{cosh(z/\lambda_L)}{cosh(t/2\lambda_L)} - 1 \right\} \hat{x} \tag{3}$$

where t is film thickness and applied field is along x-axis. If the vortices are localized in lines, $\vec{r}_k = z_k \, \hat{z} + kl \, \hat{y}$ in Eq. (2) where l is average distance of adjacent vortices in $\hat{y}$-direction and the the spatial magnetic field due to the vortices will be

$$\vec{B}_V = \frac{\Phi_o}{2\pi\lambda_L^2} \sum_{k=-N/2}^{k=N/2} \sum_{n=-\infty}^{n=\infty} (-1)^n K_0 \left\{ \frac{\sqrt{(z - nt - (-1)^n z_k)^2 + (y - kl)^2)}}{\lambda_L} \right\} \hat{x} \tag{4}$$

where K_0 is a modified Bessel function of the first order. For simplifying the free energy calculation, previous studies [4,18] have used an approximation which is valid only for a

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limit of $\lambda_L \gg a$ film thickness. Since the approximation is not applicable for our system ($\lambda_L < t$), we have to count term by term in the summation of Eq. (4).

For the free energy calculation, we need two characteristic lengths, London penetration depth and coherence length. $\lambda_L \simeq 1800$ Å for the Nb(72Å)/Al(20Å) multilayer was determiend by SPNR. The coherence lenght could be obtained by measuring H_{c1}. As the field applied parallel to the surface, the low critical field can be estimated by using the London theory [2,16]. With assuming that a vortex first enters a thin superconducting film as the free energy is zero at z where the vortex is placed, the lower critical field is

$$H_{c1} = \frac{\Phi_o}{2\pi\lambda_L^2} \frac{1}{1 - cosh(z/\lambda_L)/cosh(t/2\lambda_L)}$$
$$\times \left\{ K_0\left(\frac{\xi}{\lambda_L}\right) + \sum_{n=1}^{\infty}(-1)^n K_0\left(\frac{|z - nt - (-1)^n z|}{\lambda_L}\right) \right\} \tag{5}$$

We assum that vortices first enter the superconductor, as the free energy is zero at the surface, e.q., $z = t / 2 - \xi$ in Eq. (5) [17]. Based on the magnetization measurement, $H_{c1} = 1200 \pm 200$ Oe and ξ is calculated to be $\sim$113 Å. Although the Nb(72Å)/Al(20)Å multilayer is an anisotropic superconductor, an anisotropy of a Nb(100Å)/Cu(100Å) multilayer, ξ_y/ξ_z, was 1.23 [4], where ξ_y and ξ_z are the coherence lengths of in-plane and out of plane respectively. As comparing configuration of our specimen to Brongermas's one, the asumption of an isotropic superconductor for the calculation would not be seriously wrong.

Fig. 7 shows the minimum free energy calculation. For the calculation, it is assumed that vortices are localized in a central line ($t / 2$) (dashed line) and two lines ($t / 3$ and $2t / 3$) (solid line), as shown in the inset. At a given field, the minimum free energy was determined by varying the density of vortices only. At small fields, the free energy of the system for 1 row is smaller than for 2 rows whereas above 2200 Oe it is reverse. It means that the vortices more likely stay in 2 rows than 1 row for H > 2200 Oe. This calculation agrees well with the first peak in the magnetization measurement, as shown in Fig. 1 top and strongly suggests that the peak is due to a vortex line transition from 1 row to 2 rows. The inset at upper right corner shows magnetization which corresponds to the minimum

free energy. There is the second transition $(2 \rightarrow 3)$ at ~ 4000 Oe that is also consistent with the second peak in the *M-H* curve.

The calculation shows that vortex density of 40 μm^{-2} at 1500 Oe and 53 μm^{-2} at 2000 Oe will satisfy the condition of minimizing the free energy with 1 row of vortices in this system. From SPNR measurements, it is found to be ~ 30 μm^{-2} at 1500 Oe, ~ 45 μm^{-2} at 2000 Oe and ~ 56 μm^{-2} at cycled 2000 Oe. The smaller vortex densities at ascending fields can be understood in terms of the surface barriers because the minimizing free energy calculation does not count the barriers. Since the vortex densities at ascending fields are smaller than the maximum vortex density for 1 row, the vortices could stay in a central line however at the cycled field, the vortex density found by SPNR is slightly higher than the the maximum vortex density for 1 row. Thus they can not stay in a single row. It means that the vortex line transition fields can be shifted to a lower field for descending field, as the contribution of the surface barrier is important. It has been experimentally observed by J. Sutton *et al.* [5].

V. MAGNETIZATION AT SMALL TILTED FIELD

As the field is tilted with a small angle, the delay of vortex entrance due to the surface barrier vanishes because the perpendicular component of applied field helps the vortex ingress at a small field. Figure 8 shows the magnetization at different tilt angles. There is a peak at H $\simeq 2250$ Oe from Nb(72Å)/Al(20Å) film without depending on the tilt angle ($\theta < 3.5^o$). However we find another peak at ~ 950 Oe of the tilted field. It is the first observation that the first peak is missing at no-tilted field. One could easily overlook that the first peak does not come from the vortex line transition. Since it is a thin film, vortices can not enter the superconductor until the applied field is stronger than the surface barrier field. At a tilted field, however, vortices can overcome the surface barrier under support by the perpendicular component of the field even with a small field. Therefore the vortex line transitions could be missing at no-tilted field. This scenario could work only for that

the surface barrier field is larger than the vortex line transition fields. That is not this case because the measured surface barrier field for the specimen is about 1200 Oe and SPNR measurement shows 1 row of vortices at ascending fields of 1500 and 2000 Oe. Also the calculation for minimizing the free energy suggests that the first vortex line transition may occur at ~2200 Oe. Thus, we suspect that the first peak at the tilted field comes a vortex line transition.

Using Eq. (5), H_{c1} of this system under the equilibrium condition where vortices first enter the superconducting film as the free energy is zero at the middle of the film, e.q., $z = 0$ in Eq. (5), is calculated to be ~850 Oe. That is very comparable to the first peak at the tilted field. It might suggest that the peak is due to the lower critical field which is paralle to the surface ($H_{c1\parallel}$). At a tilted field ($\theta > 1^o$ for this system), the first vortex entrance is determined by $H_{c1\perp}$ instead of $H_{c1\parallel}$ because for a thin film superconductor, $H_{c1\perp}$ is much smaller than $H_{c1\parallel}$ [19]. For $H sin\theta$ ($H_{\perp}$) $> H_{c1\perp}$, vortices could enter the superconductor and might stay along the applied field due to the dragging force from the applied field. However the free energy still does not allow the vortices running parallel to the surfaces. When the applied field ($H cos\theta$) is increased with passing beyond $H_{c1\parallel}$, vortices sightly rotate to parallel to the surfaces, connect the pieces, and make long threads. In this scenario, however, the magnetization might be just a little changed because the field is applied with a small tilt angle. However we find that a large demagnetization effect enhances the change by more than two orders of magnitude because of the thin film geometry. The demagnetization of the multilayers is discussed in detail below.

Figure 8 (b) and (c) show the magnetization from the multilayers at 4.5 K. The magnetization from Nb(100Å)/Al(20Å) also shows that the first peak is missing at no-tilted field whereas it is observed at 600 Oe of a tilted field. That agrees well with $H_{c1\parallel} = 600$ Oe calculated by using Eq. (5) ($z = 0$), and $\lambda_L = 1800$ Å and $\xi = 113$ Å. The second and third observed peaks, ~1400 and ~2450 Oe, can also be compared to the vortex line transitions, $1 \rightarrow 2$ (1450 Oe) and $2 \rightarrow 3$ (2650 Oe) respectively estimated by the model calculation. That is another evidence that the first peak at a tilted field comes from the vortex rotation instead

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of the vortex line transition. At 4.5 K, two peaks are observed at 845 and 2125 Oe from Nb(72Å)/Al(20Å). The first peak near 845 Oe appears without depending on the tilt angle. It implies that the superconductor is soft and the surface barrier is negligible at the temperature. Since the peak positions are not very sensitive to the temperature that is consistent with previous measurements [4,9], we might also conclude that the first peak comes from the vortex rotation at $H_{c1\parallel}$. The peaks from the Nb(72Å)/Al(20Å) and Nb(100Å)/Al(20Å) multilayers were carefully measured at different temperatures and tilt angles and summarized in table VI. Table VI shows that the vortex line transitions (2nd and 3rd peaks) occur at smaller fields for a thicker film superconductor because vortices have relatively more space to the surfaces in a thicker film and rearrange for spatial commensuration at a smaller field [3,5,10].

Demagnetization factors of the multilayers are quantitatively determined in the Meissner regime. In the regime, slopes of the magnetization were measured as a function of tilt angle, as shown in Fig. 9. The solid lines are a best fit to data with a model for the demagnetization of a thin superconducting film [15]. The demagnetization factors of Nb(72Å)/Al(20Å) are found to be 0.9986 ± 0.0011 at 2 K and 0.9935 ± 0.0007 at 4.5 K while it is 0.992 ± 0.0034 for Nb(100Å)/Al(20Å) at 4.5 K. Those can be compared to theoretical calculations, 0.993, 0.9942 and 0.9934 respectively for our sample geometries [20]. For $H < H_{c1\parallel}$, the perpendicular magnetic field due to vortices is $n\Phi_{eff}sin\theta/(1 - N)$ where n is number of vortices per unit area, Φ_{0eff} is the effective flux due to the images and N is the demagnetization factor. As the vortices rotate parallel to the surface at $H_{c1\parallel}$, the perpendicular magnetic field will vanish. As assumed that a single vortex per μm^2 rotates parallel to the surfaces at the tilt angle 2.5^o, the difference of a few Gauss for our sample geometry contributes to the SQUID magnetization measurement.

VI. CONCLUSIONS

Vortex pinning is an important subject for practical application of current transportation. With only thin film geometry where vortices place parallel to the surfaces, the vortex-surface interaction could be studied. We performed SPNR measurements on a Nb/Al multilayer to directly determine the density and distribution of vortices. SPNR shows that the vortices in a Nb/Al multilayer are localized near the central line below the first peak in the *M-H* curve at the ascending field meanwhile vortices have more broadening of the distribution at the descending field. The SPNR measurement is consistent with the magnetization measurement and also a model calculation of minimizing Gibbs free energy. As the field is applied with an angle, another peak which is missing at no-tilted field is first time observed. Comparing the peak to a model calculation of $H_{c1\parallel}$, we conclude that the first peak at a tilted field comes from the vortex rotation instead of vortex line transition at $H_{c1\parallel}$.

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FIG. 1. shows magnetization measured from Nb/Al multilayers at 2 K. The data of Nb(100 Å)/Al(20 Å) and Nb(130 Å)/Al(20 Å) were shifted down along the y axis for clarity. The small arrows indicate the peaks and the big arrows points the direction of the measurements.

FIG. 2. X-ray reflectivity was measured from the Nb(72Å)/Al(20Å) multilayer at atmosphere. Dotted line is data and solid line is a best fit.

FIG. 3. (a) shows grazing angle reflectivities for spin up and spin down neutrons from a Nb(72Å)/Al(20Å) multilayer measured as a function of q at 700 Oe and 2 K. The solid line is a best fit. (b) shows $\Delta R/\overline{R}$ (described in the text) obtained from the data in (a). The solid line is a best fit and shows that the London penetration depth of the multilayer is $\sim$1800 Å.

FIG. 4. shows $\Delta R/\overline{R}$ measured from a Nb(72Å)/Al(20Å) multilayer at ascending 1500 Oe (a) and 2000 Oe (b) under 2 K. The lines are a best fit with assuming different distributions of vortices.

FIG. 5. (a) shows $\Delta R/\overline{R}$ measured from a Nb(72Å)/Al(20Å) multilayer at cycled field 2000 Oe under 2 K. The lines are a best fit with assuming different distributions of vortices. (b) shows the neutron scattering density profile that is corresponding to 2 rows of vortices in (a). The inset is a vertical expansion.

FIG. 6. shows $\Delta R/\overline{R}$ at 1500, 2000 and (cycled) 2000 Oe and the solid lines are a best fit with a Gaussian distribution of vortices.

FIG. 7. shows minimum Gibbs free energy as a function of applied field with assuming 1 row (dashed line) and 2 rows (solid line) of vortices. The assumed locations of vortices are shown in the inset at lower left. The inset at upper right shows the magnetization corresponding to the minimum free energy.

FIG. 8. Magnetic moments were measured from Nb/Al multilayers at different tilt angles and different temperatures. The arrows in (a) indicate the direction of measurement. Data in (b) and (c) were taken along the same direction of measurement in (a). The lines are a guide to the eye.

FIG. 9. shows the slopes of magnetic moment below H_{c1} as a function of tilt angle. The solid lines are a best fit with a model [15]. The data (open circle and solid triangle) are shifted down along the y axis for clarity.

TABLE I. Least-χ^2 fit at 1500 Oe

	1 row	2 rows	Uniform
χ^2:	2.788 (30 μm^{-2})	2.974 (30 μm^{-2})	3.499 (35 μm^{-2})

TABLE II. Least-χ^2 fit at 2000 Oe

	1 row	2 rows	Uniform
χ^2:	2.945 (45 μm^{-2})	2.976 (45 μm^{-2})	3.084 (60 μm^{-2})

TABLE III. Least-χ^2 fit at cycled 2000 Oe

	1 row	2 rows	Uniform
χ^2:	1.855 (50 μm^{-2})	0.969 (56 μm^{-2})	1.498 (72 μm^{-2})

TABLE IV. Results of SPNR measurements

H (Oe)	Distribution	Density per μm^2	$M_\parallel$ (G)	$\bar{M}$ (G)[a]
1500	1 row	30 ± 6	-51 ± 17	-66.6 ± 7
2000	1 row	45 ± 6	-57 ± 17	-62.8 ± 6
2000(cycled)	2 rows	56 ± 2	-42.5 ± 5	83 ± 8

[a]Magnetization directly converted from SQUID data in Fig. 8 (a) open circle with no adjustable parameter.

TABLE V. Least-χ^2 fit with a Gaussian distribution of vortices

H (Oe)	χ^2	FWHM (Å)	vortex density (μm^{-2})	$M_\parallel$ (G)
1500	2.056	510 ± 51	33 ± 3	-47 ± 9
2000	2.077	530 ± 29	47 ± 3	-58 ± 9
2000 (cycled)	0.774	700 ± 23	55 ± 2	-42 ± 6

TABLE VI. Peak positions(Oe)

Configuration of multilayer	1st	2nd	3rd
Nb/[Al(20Å)/Nb(72Å)]×20	950(2K, 4.5K)	2250(2K, 4.5K)	3900(2K)
Nb/[Al(20Å)/Nb(100Å)]×20	650(4.5K)	1400(2K, 4.5K)	2450(2K, 4.5K)

Reflectivity vs q (Å⁻¹)

Nb(180Å)/[Al(20Å)/Nb(72Å)]×20/Si

data · · · · · ·
fit ——

(a) H = 700 Oe, T = 2 K

Reflectivity, spin up (open circles), spin down (filled circles)

(b) $\lambda_L = 1800 \pm 200$ Å

$\Delta R / \bar{R}$ vs q (Å^{-1})

(b) H = 1500 Oe, FWHM = 510 Å; (b) H = 2000 Oe, FWHM = 530 Å; (c) H = 2000 Oe (cycled), FWHM = 700 Å