A magnetic vortex is a flux closure domain structure in a soft magnetic element of submicron lateral size or smaller, which can also be present in a continuous magnetic thin film. The magnetic vortex structure exhibits two characteristics of a magnetic domain structure: an in-plane curling magnetization, either clockwise or counterclockwise (chirality), and a perpendicular magnetization, either clockwise or counterclockwise (polarity), which is called the vortex core. From a technological point of view, this binary state of the vortex core can be used for information storage, and is promising for use in future nonvolatile data storage devices. Other possible applications of the vortex core switching are in a spin wave sensor, a physical random number generator such as “spin dice”, and other areas. However, the vortex core is very stable, requiring a DC magnetic field of more than 2.5 kOe to switch the core polarity. Recently, various core switching techniques using the magnetic field pulse or the spin current have been proposed to overcome the huge energy barrier to the core switching. In these methods, the core is switched by nucleating and annihilating a vortex–antivortex pair; however, a higher energy is still necessary, particularly, to control the core switching using a field pulse or a spin current pulse.

To reduce the core switching energy, we focus on utilizing a Pac-man (PM)-shaped disk. The PM disk has an open slot extending from the center to the circumference; as a result, the core can be annihilated and nucleated using that part. In early investigations using the PM disk, Park et al. observed the magnetic domain produced by changing the notch angle. The vortex state is stable in the PM disk. However, the core switching energy is reduced by 72% compared with that of a circular disk with the same diameter and thickness. However, the core switches irregularly with respect to both the field pulse amplitude and duration. This irregularity is induced by magnetization oscillations that arise owing to the excitation of spin waves when the core annihilates. We show that the core switching can be controlled with the assist magnetic field and by changing the waveform. 

We report on the switching of the magnetic vortex core in a Pac-man disk using a magnetic field pulse, investigated via micromagnetic simulations. The minimum core switching field is reduced by 72% compared with that of a circular disk with the same diameter and thickness. However, the core switches irregularly with respect to both the field pulse amplitude and duration. This irregularity is induced by magnetization oscillations that arise owing to the excitation of spin waves when the core annihilates. We show that the core switching can be controlled with the assist magnetic field and by changing the waveform. © 2014 The Japan Society of Applied Physics

Fig. 1. (a) Simulation model of PM disk. The notch depth and notch angle are \( d = 80 \text{ nm} \) and \( \theta = 25^\circ \), respectively. The diameter and thickness are \( D = 200 \text{ nm} \) and \( h = 40 \text{ nm} \), respectively. The red dotted square shows the notch edge (12 × 12 nm²). (b) Waveform of square field pulse with \( H_x = 100 \text{ Oe} \) and \( \tau_p = 2.00 \text{ ns} \). (c–f) Snapshots of PM disk at each time \( t \). (c) Initial state, (d) before annihilation, (e) after annihilation, and (f) after nucleation. The rainbow colors indicate the direction of the in-plane magnetization component. The sense of the curl of the in-plane magnetization is counterclockwise. The inset in (e) shows the snapshot of the magnetization of \( m_z \) (white: \( m_z = +1 \), black: \( m_z = -1 \)) at \( t = 1.50 \text{ ns} \).

A three-dimensional micromagnetic model was used in the simulation. Figure 1(a) shows the PM disk that was used. The notch depth from the circumference and the notch angle were defined as \( d \) and \( \theta \), respectively. A field pulse was applied in the \( x \)-axis direction. The diameter (\( D \)) and thickness (\( h \)) of the PM disk were 200 and 40 nm, respectively. Typical material parameters for Permalloy were used, as follows: exchange stiffness constant \( A = 1 \times 10^{-6} \text{ erg/cm} \), saturation magnetization \( M_s = 800 \text{ emu/cm}^3 \), magnetocrystalline anisotropy \( K_u = 0 \), and Gilbert damping constant \( \alpha \).
the nucleated core is the same as the sign of $\alpha = 0.01$. The PM disk was divided by a rectangular prism with dimensions of $2 \times 2 \times 2.5 \text{ nm}^3$. The lateral and vertical dimensions (2.0 and 2.5 nm) are safely below the exchange length of Permalloy ($\sim 5 \text{ nm}$). The simulations capture the effects from the vortex fine structure inside the bulk material, such as breathing or meandering, which may play an important role in the switching process.\cite{2,21}

Figures 1(c) to 1(f) show snapshots of the core switching of the PM disk using a field pulse with an amplitude of $H_p = 100 \text{ Oe}$, a duration of $t_p = 2.00 \text{ ns}$, and rise and fall times of 0 ns [Fig. 1(b)]. In the remanent state, the direction of the vortex core magnetization is upward [white color in Fig. 1(c)]. The core moves to the notch with the gyrotropic mode of the field pulse\cite{22} [Fig. 1(d)], and it annihilates at the notch edge [Fig. 1(e)]. After the field pulse is cut off, the downward core (black color) nucleates from the part of the notch edge [Fig. 1(f)] and moves to the disk center with the gyrotropic mode.

Figure 2(a) shows a diagram of the core switching in the PM disk as a function of the amplitude and duration of the field pulse. Here, the pulse duration step is 0.01 ns. The core switches in the blue regions of the diagram; in contrast, it does not switch in the white regions. In the blue regions, it annihilates by the same mechanisms as those shown in Figs. 1(c)–1(e). In Fig. 2(a), the core switches irregularly with respect to both the field pulse amplitude and duration. To clarify the reason for this, we investigated the time evolution of the averaged magnetization in the perpendicular direction $m_z$ and its time derivative $d(m_z)/dt$ at the notch edge region before and after the field pulse is cut off [Figs. 2(b) and 2(c)]. $m_z$ changes markedly with the core nucleation. It is expected that the core nucleation time can be obtained from the time derivative. It is also expected that the time necessary for core nucleation can be obtained from the interval between the field pulse cut-off time and the core nucleation time. Here, the notch edge region is the red dotted square region in Fig. 1(a) ($12 \times 12 \text{ nm}^2$). The size of this region is almost the same as the vortex core size. The core switches (downward core appears) in Fig. 2(b) ($t_p = 6.00 \text{ ns}$) and it does not switch (upward core appears) in Fig. 2(c) ($t_p = 5.90 \text{ ns}$). In Fig. 2(b) [Fig. 2(c)], $m_z$ and $d(m_z)/dt$ have small oscillations before the field pulse is cut off, whereas $d(m_z)/dt$ decreases (increases) markedly about 0.05 ns after $t_p$, then $m_z$ decreases (increases). This time lapse of 0.05 ns is almost the same in all cases. The direction of the nucleated core is the same as the sign of $\langle m_z \rangle$ at 0.05 ns after the field pulse. A negative (positive) $\langle m_z \rangle$ creates a downward (upward) core, meaning that the core switches (does not switch). We define this time lapse as the nucleation time.

To investigate the relationship between $\langle m_z \rangle$ and the direction of the nucleated core in more detail, we compared the time evolutions of $\langle m_z \rangle$ (black line) and the core switching regions up to $t_p = 6.00 \text{ ns}$ with $H_p = 100 \text{ Oe}$ [Fig. 2(d)]. The blue areas show the core switching regions, and the red area shows the dispersion of $m_z$ in the red dotted square region in Fig. 1(a). Here, the time of $\langle m_z \rangle$ and the dispersion are shifted by $-0.05 \text{ ns}$ (nucleation time). Spin waves appear when the core annihilates ($t = 0.84 \text{ ns}$), then $m_z$ oscillates intensively. The oscillations gradually dampen with time. Figure 2(e) shows the time evolution of $\langle m_z \rangle$ and the core switching regions between 2 and 3 ns [red dotted square region in Fig. 2(d)]. The core switching regions (blue) and nonswitching regions (white) almost agree with the black line in the negative and positive $\langle m_z \rangle$ regions in Figs. 2(d) and 2(e). The shifts between the line of $\langle m_z \rangle$ and the core switching (nonswitching) regions can be explained by considering the dispersion of $m_z$. These results show that the sign of $\langle m_z \rangle$ at 0.05 ns after the field pulse determines the direction of the nucleated core, and the irregularity of the core switching in Fig. 2(a) is an effect of the spin waves generated by the core annihilation. We mentioned that the spin waves are excited by the core annihilation, and the directions of the nucleated core are determined by the spin waves. We estimated the wave numbers ($k$) and frequencies ($f$) of the spin waves just after core annihilation to be $k \sim 0.18 \text{ nm}^{-1}$ and $f \sim 30 \text{ GHz}$, respectively. These are the same values as those of the spin waves from the annihilation of a vortex–antivortex pair.\cite{8} However, most of the spin waves are

Fig. 2. (a) Diagram of core switching as a function of field pulse duration and amplitude in PM disk. The pulse duration step is 0.01 ns. The core switches in blue regions and does not switch in white regions. (b, c) Time evolution of $\langle m_z \rangle$ (red line) and $d(m_z)/dt$ (blue dotted line) at notch edge [red dotted square in Fig. 1(a)] at approximately $t = 6 \text{ ns}$ with $H_p = 100 \text{ Oe}$. (b) The core switches (downward core appears) at $t_p = 6.00 \text{ ns}$. (c) The core does not switch (upward core appears) at $t_p = 5.90 \text{ ns}$. (d) Time evolution of $\langle m_z \rangle$ (black line) up to $t = 6.00 \text{ ns}$ with $H_p = 100 \text{ Oe}$. The red gradation and blue regions are the dispersion of $m_z$ and core switching regions, respectively. (e) Time evolution of $\langle m_z \rangle$ and core switching regions between 2 and 3 ns. (f) Frequency distributions of excitation spin waves in PM disk obtained from their Fourier-transformed spectra ($t = 1.00-6.00 \text{ ns}$) when field pulse is applied with $H_p = 100 \text{ Oe}$ and $t_p = 6.00 \text{ ns}$.
the PM disk. We also estimated the wave number in the PM disk and the circular disk with the same diameter and thickness, which are 90 and 320 Oe, respectively. The minimum switching field is reduced by 72% in the PM disk.

The switching field decreases when using the PM disk; however, the core switches irregularly with respect to both the field pulse amplitude and duration, as shown in Fig. 2(a). To control the core switching, we applied the assist field, which is a DC magnetic field in the perpendicular direction, and changed the waveform of the field pulse to control the switching. Figure 3(a) shows a diagram of the core switching with a square field pulse with an assist field of 50 Oe. The core switches irregularly in the short-pulse case; in contrast, the core switches regardless of the pulse duration for \( t_p > 4.52 \) ns and \( H_x = 100 \) Oe. We define this pulse duration as \( t_p^0 \) (here, \( t_p^0 = 4.52 \) ns). Figure 3(b) shows the time evolution of the magnetization up to \( t_p = 6.00 \) ns with \( H_z = 100 \) Oe. Since the core nucleation time is 0.05 ns, which is the same as that shown in Figs. 2(b) and 2(c), the time of \( \langle m_z \rangle \) and its deviation are shifted by \(-0.05 \) ns in Fig. 3(b), as shown in Figs. 2(d) and 2(e). Although this figure is similar to Fig. 2(d), \( \langle m_z \rangle \) has a negative value (downward) in almost all cases for \( t > 3.16 \) ns. This shows that the direction of the nucleated core is the same as the direction of the assist field for \( t_p > 3.16 \) ns. [We note that a positive \( \langle m_z \rangle \) appears at approximately \( t \approx 3.84 \) ns. This can also be explained by considering the dispersion of \( m_z \) as in Figs. 2(d) and 2(e).]

Thus, the oscillations of \( \langle m_z \rangle \) can be controlled by the assist field after a lapse of a predetermined amount of time, so the core switching can be controlled with the assist field for \( t_p > t_p^0 \). We investigated the relationship between the assist field and \( t_p^0 \) and determined the values of \( t_p^0 \) for assist field strengths of \(-25\), \(-50\), and \(-100\) Oe as 5.42, 4.52, and 3.56 ns, respectively.

Next, we changed the field pulse form to a sawtooth pulse with an assist field of \(-50\) Oe [Fig. 3(c)]. Here, \( t_p^0 \) is reduced to 2.81 ns. Figure 3(d) shows the time evolution of \( \langle m_z \rangle \) with \( H_z = 100 \) Oe and \( t_p = 6.00 \) ns. The downward core nucleates before the field pulse is cut off (\( t \approx 2.50 \) ns). The switching finishes at \( t \approx 3.50 \) ns, since the duration of the core switching becomes longer owing to the effect of the field pulse. After the core switching, the core moves around the disk center in the gyrotropic mode; hence, \( \langle m_z \rangle \) of the notch edge increases when the core approaches the edge of the disk. Note that the center of the \( \langle m_z \rangle \) oscillations (peak to peak) decreases with time from \( t \approx 2.00 \) ns, and \( \langle m_z \rangle \) becomes negative just before the core nucleation. This shows that the shape of the field pulse affects the time evolution of the out-of-plane magnetization \( \langle m_z \rangle \), and the assist field combined with the sawtooth field pulse seems to push the out-of-plane component further down in comparison with the square field pulse. In Fig. 3(c), the core does not switch irregularly at approximately \( t_p \approx 1\)–2 ns. This is due to the interactions between the \( \langle m_z \rangle \) oscillations and the reflected first spin waves from the disk edge, which are excited by the core annihilation. We also investigated the core switching with a sawtooth field pulse with a contrary slope (not shown). In this case, the core switches for \( H_z > 140 \) Oe; however, it switches irregularly, similarly to what is seen in Fig. 2(a), under the same field and pulse duration conditions. Here, we confirmed the effect of the thermal fluctuations on the core switching. \( t_p^0 \) is 2.80 ns and the minimum switching field is not changed...
at $T = 300\,\text{K}$. This result shows that the thermal effect is negligible.

Finally, we investigated the core switching mechanisms when changing the notch depth from 30 to 98 nm, in steps of 2 nm, and changing the angle from 5 to 50°, in steps of 5°, as shown in Fig. 4(a). The figure shows that the switching mechanism is less dependent on the notch angle; however, it is strongly dependent on the notch depth. The mechanism can be classified into three patterns, as shown in Fig. 4(a): (1)–(3). Figures 4(b) to 4(j) show snapshots of the magnetization $m_z$ (white: $m_z = +1$, black: $m_z = -1$). The notch angles and depths are (1) (b–d): $\theta = 25^\circ$, $d = 52\,\text{nm}$, (2) (e–g): $\theta = 25^\circ$, $d = 72\,\text{nm}$, and (3) (h–j): $\theta = 25^\circ$, $d = 92\,\text{nm}$, respectively. Here, we set the time to be $t = 0.00\,\text{ns}$ when the field pulse is cut off. In the case where the notch depth is small (1), the core switches [Fig. 4(d)] with the nucleation and annihilation of the $V$–$AV$ pair. Because the position of the created core is far from the disk center, the core moves at a high speed and it reaches the critical velocity ($v_c \sim 260\,\text{m/s}$). At the critical velocity, the $V$–$AV$ pair is nucleated and annihilated, and finally, the core switches. In the case of notch depth (2), the switching mechanism is the same as that shown in Figs. 1(c)–1(f). The nucleated core at the notch edge moves toward the center of the disk while maintaining the core polarity [Figs. 4(e)–4(g)]. In the case where the notch depth is large (3), the core is not created [Figs. 4(h)–4(j)]. In this shape, the single domain and vortex states correspond to two distinct minima separated by an energy barrier, as a result, the core cannot be created automatically from the single-domain state. These results show that the switching mechanism strongly depends on the notch depth, and the proper notch depth should be chosen to achieve the core switching.

In this letter, we have shown vortex core switching in a PM disk using a nanosecond range field pulse via micromagnetic simulations. The minimum vortex core switching field of the PM disk is reduced by 72% compared with that of a circular disk with the same diameter and thickness. However, the vortex core switches irregularly with respect to both the field pulse amplitude and duration. This irregularity is induced by magnetization oscillations arising from the spin waves caused by the core annihilation. The core switching can be controlled using an assist magnetic field and a sawtooth field pulse. Moreover, we also investigated the core switching mechanisms classified into three categories on the basis of notch depth, and show that the proper notch depth should be chosen to produce the core switching. These results will be useful for designing the cell structure of the vortex core memory.

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