Non-magnetic materials exhibiting large spin-Hall effect (SHE) are eagerly desired for high-performance spintronic devices. Here, we report that non-equilibrium Cu-Ir binary alloys with compositions beyond the solubility limit are candidates as spin-Hall materials, even though Cu and Ir do not exhibit remarkable SHE themselves. Thanks to non-equilibrium thin film fabrication, the Cu-Ir binary alloys are obtained over a wide composition range even though they are thermodynamically unstable in bulk form. We investigate the SHE of Cu-Ir by exploiting a combinatorial technique based on spin Peltier imaging, and find that the optimum Ir concentration for enhancing SHE is around 25 at.%. We achieve a large spin-Hall angle of 6.29 ± 0.19% for Cu_{76}Ir_{24}. In contrast to Cu-Ir, non-equilibrium Cu-Bi binary alloys do not show remarkable SHE. Our discovery opens a new direction for the exploration of spin-Hall materials.
Generation and detection of spin current ($J_s$), which is the flow of spin angular momentum, are the keys for spintronics. In order to improve the device performance, highly efficient conversion between charge current ($J_c$) and $J_s$ is indispensable. A way for the conversion from $J_c$ to $J_s$ is to exploit the spin-Hall effect (SHE)\(^1\)–\(^5\), which is expressed as

$$J_s = \left( \frac{\hbar}{2e} \right) \alpha_{SH} [s \times J_c], \quad (1)$$

where $J_c$ and $J_s$ are charge current density and spin current density, respectively, $\alpha_{SH}$ is the spin-Hall (SH) angle, $\epsilon$ (<0) is the electric charge of an electron, $\hbar$ is the reduced Planck constant, and $s$ is the quantization axis of electron spin. When $J_s$ flows in a nonmagnet with large spin–orbit interaction, up-spin and down-spin electrons are scattered in opposite directions. This results in a $J_s$ flow without a net charge current flow in the transverse direction to $J_c$. Equation (1) means that $\alpha_{SH}$ corresponds to the conversion efficiency, and a nonmagnet showing large $\alpha_{SH}$ is a building block of contemporary spintronics.

Many recent studies have been devoted to the materials development to get larger $\alpha_{SH}$, and found a variety of SH materials, which are not only limited to nonmagnetic metals\(^3\) but also include topological insulators\(^6\)–\(^7\), and ferromagnets\(^8\)–\(^13\). Among them, heavy metals such as Pt\(^{14}\)–\(^{16}\), T\(_3\)\(^{17}\)–\(^{18}\), and W\(^{19}\) are representatives of SH materials at present because those simple heavy metals have potential to be incorporated into the existing spintronic device architecture. Apart from the usage of elemental nonmagnetic metals, element doping and alloying are also effective ways to develop SH materials, e.g. Cu–Ir\(^{20}\)–\(^{24}\), Cu–Bi\(^{25}\), Cu–Pt\(^{26}\)–\(^{28}\), Au–Pt\(^{29}\)–\(^{30}\), and Au–W\(^{31}\). Cu–Ir system is an interesting SH material because neither Cu nor Ir exhibits remarkable SHE. Niimi and co-workers\(^{20}\) investigated the SHE of Ir-doped Cu with the Ir concentration range between 1% and 12%, which exhibited the large $\alpha_{SH}$ of ~2.1%. They mentioned that the predominant mechanism of SHE for the Ir-doped Cu was skew scattering. It was also reported that the Cu doped with a very small amount of Bi (<0.5%) also shows even larger SHE\(^{25}\). These Cu-based SH materials are also advantageous from the viewpoint of practical applications because of its compatibility to the standard integrated circuit interconnection technology\(^{21}\). In spite of the attracting features of Cu-based binary alloys, the comprehensive study on SHE for them is very limited. This limitation for the Cu–Ir might be because the solubility limits are narrow at both Cu-rich and Ir-rich sides, which are <10%, in the Cu–Ir binary phase diagram\(^{33}\). Although Cramer et al\(^{23}\) recently reported the investigation of SHE for the Cu–Ir alloys in a wide composition range, the magnitude and the mechanism of SHE, and the detailed structures have not been understood for the non-equilibrium Cu–Ir alloys beyond the solubility limit.

In this paper, we report a comprehensive study on the SHE of Cu–Ir binary alloys by combining “high-throughput screening based on thermal imaging for composition-spred films” and “accurate evaluation using harmonic Hall voltage measurement”. We utilize the spin Peltier effect (SPE)\(^{34}\)–\(^{35}\), which is the phenomenon of a heat current generation in linear response to $J_s$ injection in a magnetic insulator/SH material junction, as a probe of the spin-charge current conversion in the SH material layer since the magnitude and the sign of temperature modulation due to the SPE ($\Delta T^{SPE}$) are determined by the spin-charge current conversion. The active infrared emission microscopy called the lock-in thermography (LIT)\(^{35}\)–\(^{41}\) allows us to visualize $\Delta T^{SPE}$, and to reveal the spatial distribution of $\Delta T^{SPE}$ in the composition-spred films. We show the magnitude of SHE is maximized at the non-equilibrium phase that is not thermodynamically stable in the bulk phase diagram. After the high-throughput screening of SH material, the $\alpha_{SH}$ value at the optimum composition is evaluated. In addition to the Cu–Ir, the non-equilibrium Cu–Bi binary alloys are also prepared and their SHE is examined for comparison.

Results
Structure of Cu–Ir composition-spred film. The Cu–Ir composition-spred films were prepared on a ferrimagnetic yttrium–iron garnet (YIG) substrate with the size of 10 mm × 10 mm by the combinatorial sputtering system (CMS-3200, Comet, Inc.). A schematic illustration of the film sample is displayed in Fig. 1a. The wedge-shaped Cu and Ir layers were alternately deposited using the linear moving shutter and the rotating substrate holder. After depositing one wedge-shaped layer the substrate was rotated by 180°, and the next wedge-shaped layer was deposited. The thickest part in each layer was designed to be 0.5 nm. In other word, one Cu/Ir pair has the thickness of 0.5 nm, where the Cu and Ir layers were naturally mixed without any heating process. Finally, we obtained the composition-spred films having the Ir concentration ($x_F$) range from 0 at.% (pure Cu) to 100 at.% (pure Ir). By repeating the deposition of 0.5 nm-thick Cu/Ir pair 20 times, 40 times, and 60 times, the samples with the total thicknesses ($t$) of 10, 20, and 30 nm, respectively, were obtained. An important point here is that all the layers were deposited at room temperature in order to prevent from the appearance of thermodynamically stable phase. In the blanket film sample used for structural characterization, the gradient of composition was formed in the length of 8.0 mm, which is laterally sandwiched with the pure Cu and Ir regions, i.e. 0.6 mm for the pure Cu, 8.0 mm for the composition-spred region, and 0.6 mm for the pure Ir. The position in the blanket film ($y_F$) was defined as shown in Fig. 1a.

Figure 1b shows the $y_F$ dependence of Ir concentration ($x_F$) for the Cu–Ir composition-spred film with $t$ = 30 nm measured by electron probe x-ray microanalysis (EPMA). It is confirmed that $x_F$ is varied with the position. Although in the Cu-rich region ($y_F$ ≤ 4 mm) $x_F$ almost linearly increases with $y_F$, the position dependence deviates from the tendency in the Ir-rich region ($y_F$ ≥ 5 mm). At present, we have no clear explanation for this rapid increase of $x_F$ at the Ir-rich region. The x-ray diffraction (XRD) profiles for $t$ = 30 nm measured at different $y_F$ are shown in Fig. 1c, where the observed peaks come from the Cu–Ir 111 reflections. It is noted that the XRD peak angle continuously shifts as $y_F$ is varied, i.e. $x_F$ is increased. In addition, no remarkable peak splitting is observed at all the positions. These facts suggest that the lattice constant of single-phase alloys is continuously varied. In other words, the Cu–Ir solid solutions are formed at the overall compositions, and the non-equilibrium phase appears at the compositions that are out of the solubility limit of the bulk phase diagram. Figure 1d displays the $y_F$ dependence of the lattice constant $a$. The $y_F$ dependence of $a$ shows the continuous change, and the plot of $a$ versus $x_F$ in the inset of Fig. 1d suggests the linear relationship between $a$ and $x_F$, meaning that the Vegard’s law\(^{42}\) is satisfied. Figure 1e shows the cross-sectional high-resolution transmission electron microscope image for $t$ = 30 nm together with the element analysis of Cu and Ir by the energy-dispersive x-ray spectroscopy for the film samples at $y_F$ = 3 mm. From the element mappings, the Cu and Ir atoms are uniformly distributed. Therefore, one sees that neither segregation nor phase separation exists remarkably.

Thermal imaging of SPE. In order to evaluate the SHE of Cu–Ir composition-spred films, we carried out the SPE measurement using the LIT. As reported previously\(^{41}\), this LIT-based SPE measurement enables us to do systematic and high-throughput
screening of SH materials. SPE is the phenomenon giving rise to the temperature modulation due to the interaction of Ir and spontaneous magnetization (M). As depicted in Fig. 2a, for the present Cu–Ir/YIG junction, Iₚ generated via the SHE of Cu–Ir interacts with M of YIG, which modulates the temperature of the Cu–Ir/YIG junction. According to the previous works on SPE, the heat current (Iₚ) generated by SPE and the resultant ΔTₜₜ is proportional to αₛₛₚₑ. Therefore, by measuring the ΔTₜₜ, one can obtain information on the magnitude and sign of the SHE of Cu–Ir.

The device for the SPE measurement is schematically illustrated in Fig. 2b. The composition-spread film was patterned into the device consisting of two wires with the width of 0.4 mm. One ends of the wires were electrically connected, such that the two wires were connected in series with Ir wires flowing along opposite directions. In the device for the SPE measurement, the gradient of composition was formed along the width of 8.0 mm as shown in Fig. 2b, and the position in the device was denoted by yₜₜ. The infrared radiation thermally emitted from the sample surface was detected while applying an ac Jₚ with rectangular wave modulation to the Cu–Ir wires. The LIT conditions for the SPE and Joule heating measurements are shown in Fig. 2c, d, respectively. The SPE signal was separated from the Joule heating contribution when the first harmonic response of the thermal images was fed without any dc current offset. For the measurement of Joule heating, on the other hand, the ac Jₚ together with a dc offset of J₀ₚ was applied to the Cu–Ir wires. Although both the SPE and Joule-heating contributions are included in the first harmonic response, the observed signals mainly come from the Joule-heating-induced temperature modulation (ΔTₜₜ) because ΔTₜₜ is much larger than ΔTₛₛₑ. Therefore, the magnitude of ΔTₜₜ provides us the information of local electric conductivity. Figure 2h plots Aₜₜ as a function of yₜₜ in the left Cu–Ir wire with t = 30 nm. Aₜₜ shows the maximum at yₜₜ ~ 1.9 mm. Next, the Joule-heating contribution is examined. Figure 2f shows the amplitude (Aₜₜ) and phase (φₜₜ) images of Joule-heating-induced temperature modulation at Jₜₜ = 1 mA and ΔJₚ = 1 mA with f = 25 Hz. These images were observed without Bₑₑₑₑ. Since Aₜₜ is increased and no sign change of φₜₜ is observed for the left and right wires, Joule heating increases the temperature of the Cu–Ir wires irrespective of the Jₚ direction, which is totally different from the SPE-induced temperature modulation. Similar to the SPE-induced temperature modulation, the spatial variation of Aₜₜ outside the wires is suppressed owing to the high f. Therefore, the magnitude of Aₜₜ provides us the information of local electric conductivity. Figure 2h plots Aₜₜ as a function of yₜₜ in the left Cu–Ir wire with t = 30 nm. Aₜₜ shows the maximum at yₜₜ ~ 2.1 mm, implying the increase in the resistance (ρ) of Cu–Ir wire at yₜₜ ~ 2.1 mm. We also evaluated ρ directly using the conventional transport measurement, which is plotted in Fig. 2i. Consequently, Fig. 2h, i revealed the position-dependent ρ values along the y direction of wire. It is noted that yₜₜ ~ 2.1 mm exhibiting the maximum Aₜₜ is the different position from yₜₜ ~ 1.9 mm for the maximum of Aₛₛₑₑ.
Spin-Hall effect probed by SPE. The $y_D$ dependence of $A^{SPE}$ allows us to qualitatively discuss the Ir concentration dependence of $\alpha_{SH}$ and SH conductivity ($\sigma_{SH}$) by assuming that the spin mixing conductance at the Cu–Ir/YIG interface and the spin diffusion length in the Cu–Ir do not show a remarkable position dependence. $\Delta T^{SPE}/j_s$ and $\Delta T^{SPE}/E$ are proportional to $\alpha_{SH}$ and $\sigma_{SH} (=\sigma_{SH}@Cu-Ir)$, respectively, where $E$ is the electric field and $\sigma_{Cu-Ir}$ is the conductivity of Cu–Ir. $\Delta T^{SPE}$ is given by the real part of the complex temperature modulation output by the LIT: $\Delta T^{SPE} = A^{SPE} \cos(\phi^{SPE})$, because the phase delay due to thermal diffusion in the SPE signal is negligibly small.35,39.

Figure 3a, b show the $\Delta T^{SPE}/j_s$ and $\Delta T^{SPE}/E$ as a function of $x_{Ir}$ for $t = 10, 20$, and $30$ nm, where $x_{Ir}$ was estimated using the position dependence of $x_{Ir}$ shown in Fig. 1b. $\Delta T^{SPE}/j_s$ exhibits the maximum value around $x_{Ir} = 25$ at.% while $\Delta T^{SPE}/E$ is monotonically decreased as $x_{Ir}$ is increased. These results suggest that $\alpha_{SH}$ is enhanced around $x_{Ir} = 25$ at.%. Figure 3c is the plot of $t$ dependence of $\Delta T^{SPE}/j_s$ for several Ir concentrations. $t = 20$ nm shows a larger $\Delta T^{SPE}/j_s$ than those for $t = 10$ and $30$ nm. We have no clear reason for this $t$ dependence at present.

In order to elucidate the mechanism of the enhanced $\alpha_{SH}$ when $x_{Ir}$ is increased up to 25 at.%, $\Delta T^{SPE}/E$ versus $\sigma_{Cu-Ir}$ is summarized in Fig. 3d, where $\sigma_{Cu-Ir}$ is plotted for $t = 10, 20$, and $30$ nm. This plot corresponds to $\alpha_{SH}$ versus $\sigma_{Cu-Ir}$. One can see that $\alpha_{SH}$ remains to be almost constant regardless of $\sigma_{Cu-Ir}$. This tendency implies that either the side jump process or the intrinsic mechanism due to the Berry curvature is a dominant mechanism for the SHE in the Cu–Ir. The details will be discussed later. An important finding is the enhanced $\alpha_{SH}$ around $x_{Ir} = 25$ at.% that is definitely outside of the solubility limit in the Cu–Ir phase diagram.33.

Quantitative analysis of spin-Hall angle. Here we evaluate the SH efficiency for the Cu$_{76}$Ir$_{24}$ alloy, which is in the composition range showing the enhanced $\alpha_{SH}$, using the harmonic Hall voltage measurement.44–48. For this quantitative measurement, we prepared a thin film consisting of Cu$_{76}$Ir$_{24}$ (t nm)|CoFeB (2 nm)|Al (2 nm) on the sapphire c-plane substrate, where the Cu$_{76}$Ir$_{24}$ is a wedge-shaped layer with $t$ in the range from 1 to 19 nm, and the CoFeB is in-plane magnetized. The thin film was patterned into the Hall bar shape as illustrated in Fig. 4a. The in-plane first harmonic ($V^0$) and the out-of-plane second harmonic voltages ($V^{2\omega}$) were detected using two lock-in amplifiers under the application of ac current with the frequency of $\omega/2\pi = 172.1$ Hz, allowing us to separately determine two kinds of torques acting on the CoFeB magnetic moment ($m$). In general, SHE gives rise to the damping-like (DL) torque pointing along $m \times (m \times s)$ with a magnitude of $B_{DL}$. Another torque mainly coming from the Rashba–Edelstein effect (REE) is called the field-like (FL) torque directed along $m \times s$ with a magnitude of $B_{FL}$. By considering the dependence of $V^0$ and $V^{2\omega}$ on the in-plane field angle ($\theta$, depicted
Using the coefficients including the anomalous Nernst effect and spin Seebeck effect, the second harmonic Hall signal due to thermoelectric effects of the orange open circles denote the measured data, and the blue curve is the result of fitting by $\cos \theta$. The green open circles denote the measured data, and the black curve is the result of fitting by $\cos 2\theta \cos \theta$ function. As seen in Fig. 4c, the $\xi_{DL}$ dependence of $\Delta T^{SPE}$ is fitted by Eq. (4). We also measured the AHE with $B_{ext}$ applied normal to the device plane (Fig. 4d), and $R_{AHE} = 1.74 \Omega$ and $B_{ani} = 0.9 \text{T}$ were obtained. The coefficient $C (D)$ as a function of the inverse of $B_{ext} + B_{ani}$ (the inverse of $B_{ani}$) is plotted in Fig. 4e (Fig. 4f), where the large $B_{ext}$ was applied to do the correct estimation of the thermo-electric contribution. From the linear fits, $B_{DL}$ and $B_{FL}$ are evaluated to be 0.74 and 0.33 mT, respectively. According to the previous papers\cite{47, 48}, the DL torque efficiency ($\xi_{DL}$) and the FL torque efficiency ($\xi_{FL}$) are given by $\xi_{DL} = \frac{\eta_{DL} M_{s}}{j_{\text{CFB}} B_{ext}}$ and $\xi_{FL} = \frac{\eta_{FL} M_{s}}{j_{\text{CFB}} B_{ext}}$, where $M_{s}$ is the saturation magnetization of CoFeB, which were experimentally obtained to be 800 kA m$^{-1}$, $j_{\text{CFB}}$ is the CoFeB layer thickness, and $j_{\text{Cu-Ir}}$ is the current density flowing in the Cu-Ir layer. With the parameters of $M_{s} = 800 \text{kA m}^{-1}$ and $j_{\text{Cu-Ir}} = 8.1 \times 10^{6} \text{A cm}^{-2}$, $\xi_{DL} = 4.5\%$ and $\xi_{FL} = 2.0\%$, which were obtained for $t = 5.8 \text{nm}$. The accuracy in the estimation of $\xi_{FL}$ should be noted here. The small $\cos 2\theta \cos \theta$ dependence in $R^{2\omega}$, which is attributed to the small $R_{PHIE}$, gives rise to the low accuracy for the estimation of $\xi_{FL}$. Also, one is aware of the apparent parabolic $1/B_{ext}$ dependence of coefficient $D$ in Fig. 4f. This is attributable to the unwanted cross talk between $B_{ext}$ and $D$ in the fitting and a small imperfection in $C$, which is probably due to the slight misalignment or the experimental uncertainty, leads to a large relative error in $D$. This is another source of the low accuracy for the estimation of $\xi_{FL}$. In contrast to $\xi_{FL}$, the estimation of $\xi_{DL}$ is not affected by the magnitude of $R_{PHIE}$. Hereafter, we will focus on the DL torque component, and evaluate $\xi_{DL}$ for the Cu$_{20}$Fe$_{80}$ from $\xi_{DL}$.

According to ref.\cite{49}, with the assumption that the interface spin transparency is $<1$ and the spin backflow is dominant at the well-ordered interface, the $t$ dependence of $\xi_{DL}$ per unit applied electric field, $\xi_{DL}^{E}/\rho$, is expressed as

$$\xi_{DL}^{E}(t) = \frac{2e}{\hbar} \sigma_{SH} [1 - \text{sech}(t/\lambda_{SD})] \left(1 + \frac{\tanh(t/\lambda_{SD})}{2\lambda_{SD} \rho \text{Re}[G_{MIX}]} \right)^{-1},$$

where $\lambda_{SD}$ is the spin diffusion length of Cu$_{20}$Fe$_{80}$ and Re$[G_{MIX}]$ is the real part of the spin mixing conductance. Using the $t$ dependence of $\rho$ (Fig. 4g), $\xi_{DL}^{E}$ is plotted as a function of $t$ in Fig. 4.
This work has three major achievements: (i) development of non-equilibrium Cu–Ir binary alloys beyond the solubility limit by the sputtering method, (ii) finding that the non-equilibrium Cu–Ir exhibits the large SHE although neither Cu nor Ir exhibits remarkable SHE, and (iii) elucidation of mechanism of SHE for the non-equilibrium Cu–Ir. Our comprehensive investigation revealed that the value of $\alpha_{\text{SHE}}$ shows the maximum around $x_{\text{Ir}} = 25$ at.%, which is much larger than the solubility limit. Even at such a non-equilibrium composition, we successfully obtained the single-phase Cu–Ir binary alloy, $\alpha_{\text{SHE}} > 6\%$ obtained for Cu$_{76}$Ir$_{24}$ is comparable to or larger than that for Pt$^5$.

Finally, we complement the mechanism of SHE for the non-equilibrium Cu–Ir binary alloy. As shown in Fig. 3d, the plot of $\Delta T^{\text{SPE}}/E$ versus $\alpha_{\text{Cu–Ir}}$ suggests that $\alpha_{\text{SHE}}$ keeps almost constant regardless of $\alpha_{\text{Cu–Ir}}$. This indicates that either the side jump process or the intrinsic mechanism due to the Berry curvature is a dominant mechanism for the SHE in the Cu–Ir. It is worth noting that Bi-doped Cu is believed to be a good SH material$^{25}$, we performed the same LIT-based SPE measurements using a Cu–Bi composition-spread film on the YIG substrate. In contrast to the Cu–Ir, the non-equilibrium Cu–Bi binary alloys do not show remarkable SHE (see Supplementary Fig. 2). According to ref. $^{25}$, doping a very small amount of Bi is effective to obtain the large SHE. On the other hand, this study examined the effect of alloying on SHE for the Cu–Bi over a wide composition range, and do not examine on the Cu-rich region with a very small amount of Bi. This is a possible reason why the present Cu–Bi does not exhibit the definite SHE. As a result, we found that the alloying is not effective for the Cu–Bi binary alloys.
that the previous work for the Ir-doped Cu reported that the skew scattering plays the dominant role for the SHE in the Ir-doped Cu with $x_{Ir} < 12$ at.%. Therefore, the present non-equilibrium Cu–Ir binary alloy exhibits the SHE totally different from the Ir-doped Cu quantitatively and qualitatively. Our discovery suggests that a non-equilibrium alloy consisting of non-magnets with negligible SHE has a potential as an SH material, and opens a new direction for the exploration of SH materials.

Methods

Fabrication of composition-spread Cu-Ir (Cu–Bi) film. The Cu–Ir (Cu–Bi) composition-spread films were fabricated on a YIG substrate at ambient temperature using DC magnetron sputtering with a base pressure of $< 10^{-6} \text{ Pa}$ and a process Ar gas pressure of 0.4 Pa. The YIG substrate consists of a 23-μm-thick single-crystalline YIG (111) film uniformly grown on a single-crystalline Gd$_2$Ga$_2$O$_4$ (111) substrate by means of a liquid phase epitaxy method. To improve the lattice matching between YIG and Gd$_2$Ga$_2$O$_4$–a tiny amount of Y in YIG is substituted by Bi. The substrate was cut into a $10 \times 10 \text{ mm}^2$ square shape. As described in the main text, the Cu–Ir composition-spread films were prepared by repeating the following three processes: (1) deposition of a wedge-shaped Cu layer using the linear moving shutter, (2) rotation of the substrate by 180°, and (3) deposition of a wedge-shaped Ir layer using the linear moving shutter, where the total thickness of a Cu/Ir pair was designed to be 4 nm. The deposition of 0.5-μm-thick Cu/Ir pair was repeated 20 times, 40 times, and 60 times for the samples with total thicknesses of 10, 20, and 30 nm, respectively. All the layers were deposited at room temperature in order to prevent from the appearance of thermodynamically stable phases. The same deposition procedure was used for the Cu–Bi composition-spread films. The Cu (Ir) layers were deposited at a rate of 0.052 nm s$^{-1}$ ($0.034$ nm s$^{-1}$). For the LIT measurement, the composition-spread film was patterned into a rectangular shape with a size of 8.0 mm $\times$ 0.4 mm by sputtering the layers through a metallic shadow mask, where the composition gradient is along the 8 mm direction. All the films were capped with a 2-nm-thick Al film to prevent oxidation. In addition to the composition-spread films, for the harmonic Hall voltage measurement, we prepared the thin film consisting of Cu$_{76}$Ir$_{24}$ (nm) CoFeB (2 nm)Al (2 nm) on the sapphire c-plane substrate. The thickness of wedge-shaped Cu$_{76}$Ir$_{24}$ layer was continuously varied from 1 to 19 nm in the lateral length of 20 mm, where the Cu$_{76}$Ir$_{24}$ layer was formed by co-sputtering of Cu and Ir. We experimented by changing the DL torffe effimicconducrs. Science 306, 1910–1913 (2004). Wunderlich, J., Kaestner, B., Sinova, J. & Jungwirth, T. Experimental observation of the spin Hall effect in a two-dimensional spin–orbit coupled semiconductor system. Phys. 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Author contributions
T.S. and K.U. conceived the idea, and planned and supervised this study. H.M. and R.M. carried out the sample preparation and the structural characterization with the help from Y.S., K.U., and T.S. The LIT measurement and its analysis were performed by H.M. and K.U. with input from R.L., and the harmonic Hall measurement was done by H.M. and Y.C.L. T.S. wrote the paper with input from K.U., R.M., Y.C.L., R.I., and K.T. All of the authors contributed to the understanding of physical mechanism.

Competing interests
The authors declare no competing interests.

Additional information
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