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Synthesis and superconductivity of In-doped SnTe nanostructures

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InₙSnₙ₋ₓTe is a time-reversal invariant candidate 3D topological superconductor derived from doping the topological crystalline insulator SnTe with indium. The ability to synthesize low-dimensional nanostructures of indium-doped SnTe is key for realizing the promise they hold in future spintronic and quantum information processing applications. But hitherto only bulk synthesized crystals and nanoplates have been used to study the superconducting properties. Here for the first time we synthesize InₓSn₁₋ₓTe nanostructures including nanowires and nanoribbons, which show superconducting transitions. In some of the lower dimensional morphologies, we observe signs of more than one superconducting transition and the absence of complete superconductivity. We propose that material inhomogeneity, such as indium inhomogeneity and possible impurities from the metal catalyst, is amplified in the transport characteristics of the smaller nanostructures and is responsible for this mixed behavior. Our work represents the first demonstration of InₓSn₁₋ₓTe nanowires with the onset of superconductivity, and points to the need for improving the material quality for future applications. © 2017 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).

Topological insulators (TIs)1,2 and topological crystalline insulators3 (TCIs) are unique states of matter with an insulating bulk and gapless surface states (SS) that are chiral and massless. The SS are robust against backscattering due to the presence of symmetries: Time reversal symmetry in TIs and crystal symmetries in TCIs. These properties make them viable choices in next generation dissipationless electronic and spintronic devices.9 More recently, a derivative of these topological materials, the topological superconductor (TSC), has garnered great interest especially in the development of topological quantum information processors.5,8 Similar to TIs, TSCs are time-reversal invariant and are predicted to host emergent Majorana states,7 which are a crucial ingredient for fault tolerant quantum computing.8

Even though the physics of TCIs and TIs has been well established, realizing the full potential of these materials, both in fundamental studies and device applications, relies on the ability to synthesize high quality, scalable nanostructures. A main challenge in topological materials synthesis is having the bulk states sufficiently gapped so that the unique electronic signatures of the SS can emerge in electronic transport studies. Growing thin films or low dimensional structures to increase the surface area to volume ratio is a way of addressing this challenge as long as the interesting properties are retained when the dimensionality is reduced.9,10 On the other hand, realizing topological superconductivity adds further challenges. Based on the available theoretical toy models,11–13 TSCs are typically designed by placing superconducting contacts onto topological materials of low

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dimensions and inducing superconducting correlations into the topological edge or SS.\textsuperscript{14-17} Another route to create emergent Majorana fermions would be to place 1D nanowires with large spin-orbit coupling on superconductors.\textsuperscript{18-20} Low-dimensional TSC structures are also a prescribed route for demonstrating fault tolerant quantum braiding operations\textsuperscript{21} and field tunable spintronic applications.\textsuperscript{4} But fabricating highly transparent superconductor-metal interfaces while retaining topological protection of the SS has been an arduous task. Although there is ongoing technical progress made,\textsuperscript{19} it is highly desirable to explore and synthesize TSC materials that are intrinsically time-reversal invariant. Recently two such materials were identified: metal-intercalated Bi\textsubscript{2}Se\textsubscript{3},\textsuperscript{22-24} and indium-doped tin telluride, In\textsubscript{x}Sn\textsubscript{1-x}Te.\textsuperscript{25-28} For metal-intercalated Bi\textsubscript{2}Se\textsubscript{3}, copper-intercalated Bi\textsubscript{2}Se\textsubscript{3} is most extensively studied with recent superconductivity reports on strontium-intercalated Bi\textsubscript{2}Se\textsubscript{3} and thallium-incorporated Bi\textsubscript{2}Te\textsubscript{3}.\textsuperscript{29-32} In\textsubscript{x}Sn\textsubscript{1-x}Te, the focus of this work, is derived from doping the TCI tin telluride, SnTe.\textsuperscript{33} Superconductivity in In-doped SnTe bulk crystals has been studied in detail.\textsuperscript{26,34-39} Previous experimental work using angle resolved photoemission spectroscopy\textsuperscript{38} has shown that the SS in SnTe remain intact after indium doping, and point contact Andreev spectroscopy on bulk crystals has shown signs of unconventional superconductivity.\textsuperscript{40} In In\textsubscript{x}Sn\textsubscript{1-x}Te nanoplates synthesized using a modified chemical vapor transport (CVT) method, a complete superconducting transition was observed.\textsuperscript{27} Experiments on nanoplates grown using vapor liquid solid (VLS) techniques with gold films as a catalyst showed that the indium doping reduced the bulk carrier mobility, revealing the SS signatures of SnTe.\textsuperscript{25}

In this work, we address and successfully accomplish a crucial step in the synthesis of TCIs by growing low-dimensional In\textsubscript{x}Sn\textsubscript{1-x}Te nanostructures with x ranging between 0.04 and 0.06, including nanowires and nanoribbons, while maintaining their superconducting properties. We use a chemical vapor deposition (CVD) method using gold nanoparticles as a catalyst. Superconducting transition temperatures ($T_c$) of $\sim$1.4-1.75 K are observed in our nanoribbons and nanowires. We find that the superconducting transition varies between nanoplates, nanoribbons, and nanowires. Nanoplates display a very sharp drop in the resistance to zero at $T_c$, whereas nanoribbons exhibit a more gradual transition at a slightly lower $T_c$. In some nanowires, we observe a saturating resistance and signs of multiple superconducting transitions in the same nanostructure. We propose that material inhomogeneity, such as indium-doping inhomogeneity and possible gold impurities, is amplified in the smaller nanostructures and gives rise to the mixed behavior in the superconducting transition. Thus, we highlight the material challenge that must be overcome for probing topological superconductivity in these reduced dimensions.

The In\textsubscript{x}Sn\textsubscript{1-x}Te nanostructures are synthesized using InTe and SnTe powders as precursors at a $\sim$2:1 ratio by weight. The experimental setup is shown in Fig. 1(a). The ground mixture of the precursors is placed at the center of a furnace and heated to 570 °C. A constant flow of ultrapure argon gas is used to carry the vaporized precursor elements downstream to SiO\textsubscript{2}/Si substrates coated with Au nanoparticles, which serve as the catalyst. The size and shape of the catalyst influences the morphology of the nanostructures; hence 20 nm Au colloidal particles (Sigma Aldrich) were used as catalysts to aid the growth of nanowires and nanoribbons. The temperature, pressure, and flow rate of the argon gas are finely tuned to obtain SnTe nanostructures with the required levels of indium doping, which ranges between 4\% and 6\%, verified by energy dispersive X-ray (EDX) spectroscopy. More details on the parameters used in the synthesis are presented in the supplementary material. We usually find nanowires and nanoribbons along with micro-crystals on the growth substrate 10-12 cm downstream from the center of the furnace (see Fig. S1 of the supplementary material). For convenience, we loosely classify the nanostructure morphologies into three types. The first two are structures that grow axially starting from the Au particles: nanowires, for structures up to 300 nm in width [Fig. 1(b), left] and nanoribbons [Fig. 1(b), center] for structures between 300 nm and 1 \( \mu \)m in width. The third type is the nanoplate [Fig. 1(b), right], which starts out by growing from the Au and then expands laterally. They are typically a few microns wide in the two lateral dimensions. An EDX spectrum of a nanoplate is shown in Fig. 1(c), displaying a distinct indium K-\( \alpha \) peak at 24.2 keV. From this, the indium doping concentration $x$ of $\sim$6\% was calculated using the same method as in our previous work.\textsuperscript{25} Figure 1(d) shows the transmission electron microscope (TEM) image of the indium-doped SnTe nanoplate and its FFT demonstrating that the cubic structure is retained after doping.
FIG. 1. Synthesis, characterization, and classification of In$_x$Sn$_{1-x}$Te nanostructures. (a) Schematic of the furnace setup used in the synthesis. (b) Optical microscope images on a SiO$_2$/Si substrate of the three different morphologies discussed in the main text: nanowire (left), nanoribbon (center), nanoplate (right). (c) EDX spectrum of a nanoplate showing the indium peak at $E = 24.2$ keV, which is used to estimate the indium doping percentage of $\sim 6.0\%$. Several nanoplates, nanoribbons, and nanowires were examined for the indium doping concentration, which ranges between 4% and 6% (with 1%–2% uncertainty). (d) TEM image and FFT generated electron diffractogram of the In-doped SnTe nanoplate demonstrating that the cubic structure of SnTe is preserved.

To electronically characterize these nanostructures, we transfer them onto freshly prepared SiO$_2$/Si substrates and fabricate four terminal devices using Cr/Au contact electrodes. For the particular nanowire sample presented here, we used Ti/Al contacts, but in this device the superconductivity of the electrodes was eliminated by applying a very small field (30 mT) above the critical field of Al. The key observations discussed in this paper are still consistent. The separation between the contact leads for all the devices was maintained around $\sim 1.5–2.0\ \mu$m. The measurements were carried out in a He-3 refrigerator with a base temperature around 0.35 K. More information on device fabrication is presented in the supplementary material. The resistance ($R$) versus temperature ($T$) curves representing each of the nanostructures are presented in Figs. 2(a)–2(c), left column. The inset shows scanning electron microscopy (SEM) images of the devices. All three nanostructures show a superconducting transition where the $T_c$ is estimated to be at the 5% drop of the normal resistance at the onset of the superconducting transition. Several devices were tested under higher current excitations and/or magnetic fields confirming that the drop in $R$ is associated with the onset of superconductivity and disappears above a critical current and field (Figs. S2 and S3 of the supplementary material). The nature of the transition however varies across the different morphologies, even when the synthesis conditions and fabrication methods are identical. The right column
FIG. 2. Superconducting transitions in the three nanostructures. (Left) $R$ vs $T$ curves. Inset shows the SEM images of the devices. The widths of the nanoribbon and the nanowire are $\sim 670$ nm and $\sim 193$ nm, respectively. (Right) Fine scan of $R$ vs. $T$ close to the $T_c$ showing the nature of the superconducting transition. (a) Nanoplate: the superconducting transition is sharp and happens within $\Delta T \sim 0.05$ K with a resistance drop to zero below $T = 2.1$ K. We note that the upturn in the resistance below 0.8 K is related to the measurement noise as the I-V curves at 1.65 K show complete superconductivity [presented in Fig. 3(a)]. (b) Nanoribbon: the superconducting transition is gradual and occurs within $\Delta T \sim 1.2$ K. The rate of transition changes around $T \sim 1.6$ K. Below $T = 0.6$ K, $R$ tends to zero. (c) Nanowire: the superconducting transition is gradual, $\Delta T \sim 1.0$ K and the resistance saturates to $R \sim 55$ $\Omega$ at the base temperature.

of Fig. 2 shows the resistance change for fine temperature sweeps closer to $T_c$. In the nanoplate devices [Fig. 2(a), right], the transition is sharp and complete, with the resistance going to zero at temperatures around $\sim 2.1$ K. We note that there is a slight upturn in the R vs T of the nanoplate device which starts around 1 K reaching a resistance of $\sim 0.04$ $\Omega$ at $T = 0.35$ K. Although reminiscent of reentrant behavior observed in granular superconductors, $\text{In_xSn_{1-x}Te}$ is a crystalline material. For low resistance measurements, noise from the measurement setup can also contribute to such artifacts.
We find that the DC $I$-$V$ characteristics for the same device at $T = 0.4$ K shows clear supercurrent and that the superconductivity is intact. Nanoribbon and nanowire devices show lower $T_c$s of $\sim 1.79$ K and $1.75$ K, respectively [Figs. 2(b) and 2(c), right], and the transition is more gradual. Moreover, for the nanowire device, we see that the resistance saturates at a finite value. For the nanoribbon, we also observe the slope of the $R$ vs $T$ changes within the transition window.

To explore these varied behaviors in detail, we study the current-voltage ($I$-$V$) behavior of the devices. The DC $I$-$V$ curves and the differential resistances as a function of the current bias ($I_{bias}$) of the same three devices at $T = 0.35$ K are shown in Fig. 3. The $I$-$V$ curve for the nanoplate device at $T = 1.65$ K clearly shows supercurrent with a critical current of $I_c \sim 168 \mu$A, which is roughly estimated by the current value at which the voltage switches from zero (superconducting state) to a finite value (resistive state). This value is lower for the nanoribbon device ($I_c \sim 3.5 \mu$A at $T = 0.35$ K) and follows the anticipated scaling of $I_c$ with sample size. In the nanowire device, the $I$-$V$ curve is nonlinear, but there is no supercurrent at the base temperature $T = 0.35$ K. The temperature and magnetic field dependence of the nanowire $I$-$V$ characteristics (Fig. S3 of the supplementary material) confirms that the non-linearity is due to the onset of superconducting-like correlations.

The differential resistance ($\frac{dV}{dI}$) vs. $I_{bias}$ unravels more information about the $I$-$V$ behavior. The $\frac{dV}{dI}$ of the nanoplate has no distinctive features except for the spike due to the abrupt switch from the superconducting zero resistance state to the normal resistive state. However, in the nanoribbon device, in addition to the switching peak, we observe an extra spike, a smaller peak that appears at $I_{bias} = 4.6 \mu$A. This peak is also related to superconductivity as verified by low field measurements. Similar to the first switching peak, it disappears as the superconductor becomes normal near the upper critical field (see Fig. S4). The upper critical fields of the nanostructures are $0.3$ T or higher as shown in Figs. S2 and S3 of the supplementary material). When driving the superconductor normal by ramping up the excitation current, current induced flux jumps can cause spikes to appear in the $dV/dI$. But such flux dynamics by vortex formation and annihilation is hysteretic and the spikes will be irreproducible when ramping the current back down towards the superconducting state.$^{41}$ In our device, the second spike is reproducible and is independent of the current sweep direction (see Fig. S5 of the supplementary material). The presence of these two distinct peaks indicates that there are at least two superconducting domains with different critical currents in the device. We note that the $\frac{dV}{dI}$ between the two peaks is higher than the normal state resistance. However, it may not be fully developed as the current step size in our measurement setup is limited to 10 nA. The $\frac{dV}{dI}$ of the nanowire device, on the other hand, shows a broader transition to the normal state and settles to a finite value at zero bias.

In superconducting thin films and nanowires, quantum suppression due to quantum phase slips can give rise to a non-zero resistance$^{43,44}$ at temperatures well below $T_c$. This explanation is found to be consistent only when the normal state resistance is close to the quantum resistance ($R_Q = \hbar/4 \times 10^2$). However, the resistances of our nanostructures are much lower than the quantum resistance. In addition, the dimensions of the nanostructures are large (>200 nm) compared to the superconducting coherence length ($\xi$) ~ 23 nm, an upper bound estimate made by studying the temperature dependence of the critical field in the nanoplate device (see Fig. S6 of the supplementary material), eliminating existence of phase slip centers in any of these nanostructures. Phase slips due to heating effects and thermal fluctuations in nanowires can also lead to a lower temperature low resistance tail. In such cases, a hysteresis is observed in the $I$-$V$ characteristics with forward and reverse current sweeps.$^{45}$ Our devices do not display such behavior.

Next, we consider the effect of the contacts. All the measurements reported here are four terminal devices. To remove any oxidation or impurities on the surface, the contact area for the electrodes was milled using Ar ions just before the metal deposition (see supplementary material for details). Despite these precautions, the contacts can still have a finite transparency and using invasive electrodes may suppress the superconducting order parameter via the antiproximity effect.$^{46}$ Nonetheless, the length of the nanowire between the voltage probes is two orders of magnitude longer than $\xi$, hence only a tiny segment $\sim \xi$ or smaller will become proximitized. Therefore, it is unlikely that proximity effects alone can explain our observations.

Another source for the quantum suppression lies in the crystalline quality of nanostructures. Quantum suppression and saturating resistances can be induced by inhomogeneity and
FIG. 3. $I$-$V$ characteristics of the nanostructures: (left) $I$-$V$ curves and (right) differential resistances as a function of $I_{\text{bias}}$. (a) Nanoplate: the $I$-$V$ curve and the $\frac{dV}{dI}$ show a large and finite $I_c \sim 168 \, \mu A$ at $T = 1.65 \, K$. (b) Nanoribbon: $I_c \sim 3.5 \, \mu A$ at $T = 0.35 \, K$ and a step-like transition is observed in the switching region. The differential resistance shows a second spike at $I_{\text{bias}} \sim 4.5 \, \mu A$, indicating a second superconducting to normal transition. (c) Nanowire: A non-linear $I$-$V$ curve is observed, but $I_c = 0$ at $T = 0.35 \, K$. No complete superconducting transition. The differential resistance shows a broader peak which indicates more gradual resistive transitions. The devices presented here are the same devices presented in Fig. 2.

In In$_x$Sn$_{1-x}$Te nanostructures, there is a critical concentration of indium, $\sim 5\%$ in our case, for superconductivity to emerge. Above the critical concentration, bulk crystals have shown an increase in $T_c$ with increasing indium doping. Thus, it is important to consider indium inhomogeneity within the nanostructures. In particular, a recent nuclear magnetic resonance studies on In-doped SnTe suggest localized impurity states induced by indium doping. During the synthesis
process, all three elements (In, Sn, and Te) dissolve in the Au catalyst, but the carefully determined growth conditions only allow SnTe crystal nanostructures to form with required levels of indium doping. Within the resolution of the EDX map, the indium doping across the nanostructures does not vary (Fig. S7 of the supplementary material). However, we find that some percentage of indium still remains in and around the Au nanoparticle (see Fig. S8 of the supplementary material). More directly, using low voltage (1 keV) surface sensitive SEM imaging, we observe regions of higher intensity contrast on In-doped SnTe microcrystals [Fig. 4(a)]. Elemental analysis on these regions using SEM-EDX shows pronounced indium presence [Fig. 4(b)]. Thus, we observe, at least on the surface of the nanostructures, inhomogeneous distribution of indium dopants. We note that we could not easily notice the indium dopant inhomogeneity on the surface using a higher electron beam voltage such as 5 keV or 10 keV (Fig. S9 of the supplementary material). As a result of this indium inhomogeneity, sub-critically doped non-superconducting and weakly superconducting micro domains can exist in the nanostructures. This can explain the mixed transport characteristics: multiple and gradual superconducting transitions and finite resistance at base temperature. Indeed, larger nanostructures such as the nanoplates can also have this inhomogeneity, but we propose that the larger dimensionality washes out the revealing transport signatures. Another possibility for inhomogeneity is gold impurities, introduced from the gold catalyst during growth. For Si nanowires grown via the VLS technique using gold particles, gold impurities have been observed and shown to degrade the transport properties. Recently, presence of gold was observed in SnTe nanocrystals grown using gold catalysts via SEM EDX. For our In-doped SnTe nanostructures using Au nanoparticles, we do not observe obvious Au EDX peaks in the nanostructures (Fig. S10 of the supplementary material). However, the lack of the obvious Au peak in the EDX spectrum does not rule out the presence of gold impurities whose concentration is expected to be small. Since gold impurities can be introduced only through the gold nanoparticles, nanowires, and nanoribbons, which were grown preferentially via VLS instead of VS (vapor solid), would have more gold impurities than nanoplates. Unfortunately, the accuracy of the EDX detector is not sufficient to reveal clearly either the indium inhomogeneity or gold impurities. High-resolution atomic imaging may provide some useful information via atomic-number (Z) contrast scanning TEM (STEM) imaging, although current nanoplates and nanoribbons may be too thick. Atom probe tomography may be necessary to study the possible indium inhomogeneity or gold impurities, which is beyond the scope of the current work.

The morphological dependence of the $T_c$ provides further evidence of doping inhomogeneity in the smaller dimensional structures. As summarized in Fig. 5, nanowires and nanoribbons in general have a lower $T_c$ than nanoplates. As per the Anderson criterion, the $T_c$ gets suppressed only when $\xi$ becomes comparable to or less than the dimension of the superconductor, which is not the case in our devices. Moreover, the indium doping levels in all these devices are around 4%-6%, eliminating the possibility of carrier density dependent $T_c$ as reported in previous studies.

![FIG. 4. Direct observation of inhomogeneous indium doping in In$_x$Sn$_{1-x}$Te. (a) SEM images of an In-doped SnTe microcrystal, which shows bright islands on the surface. The image in (a) is obtained from the region marked by yellow box in the inset. (b) SEM-EDX spectra of a bright island and its neighboring region. Compared with the neighboring region (red spectrum), the bright island (blue spectrum) shows a higher concentration of indium, indicating indium inhomogeneity. The indium peak is at $E = 3.29$ keV. The SEM images were obtained with a 1 keV incident beam voltage.](image-url)
To summarize, we developed a method that successfully synthesized nanowires, ribbons, and nanoplates of the topological superconductor candidate In$_x$Sn$_{1-x}$Te, all of which show a consistent superconducting transition. The upper critical field of these nanostructures is reasonably high (0.3 T or higher), which can be exploited in quantum interferometric studies of Andreev bound surface states. In the larger plates, we see complete superconductivity and supercurrents, whereas in some of our lower-dimensional nanoribbons and wires, we see an incomplete transition. Even though external factors such as proximitization by the contacts can cause such effects, our results point to inhomogeneous indium doping and possible gold impurities as the dominant factor. A solution to the possible inhomogeneous indium doping is to use In$_x$Sn$_{1-x}$Te precursor from a bulk In-doped SnTe crystal. Replacing the Au nanoparticles with other metallic particles such as Sn nanoparticles may solve the gold impurity issue. Atomic scale imaging, atom probe tomography, low temperature scanning probe measurements, and tunneling measurements are required to provide further insight into this observation, which is beyond the scope of the present work. Nevertheless, the ability to control dimensionality of a TSC without losing the superconducting correlations holds promise in the synthesis and study of other candidate TSCs.

See supplementary material for experimental details in synthesis, material characterization including chemical mapping, and device fabrication as well as additional figures on transport measurements.

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16 J. Wang, C.-Z. Chang, H. Li, K. He, D. Zhang, M. Singh, X.-C. Ma, N. Samarth, M. Xie, Q.-K. Xue, and M. H. W. Chan, Phys. Rev. B 85, 045415 (2012).
17 J. R. Williams, A. J. Bestwick, P. Gallagher, S. S. Hong, Y. Cui, A. S. Bleich, J. G. Analytis, I. R. Fisher, and D. Goldhaber-Gordon, Phys. Rev. Lett. 109, 056803 (2012).
18 V. Mourik, K. Zhao, S. M. Frolov, S. R. Plissard, E. P. A. M. Bakkers, and L. P. Kouwenhoven, Science 336, 1003 (2012).
19 W. Chang, S. M. Albrecht, T. S. Jespersen, F. Kuemmeth, P. Krogstrup, J. Nygard, and C. M. Marcus, Nat. Nanotechnol. 10, 232 (2015).
20 S. Nadj-Perge, I. K. Drozdov, J. Li, S. M. Frolov, S. R. Plissard, E. P. A. M. Bakkers, and L. P. Kouwenhoven, Science 336, 602 (2014).
21 J. Wang, C.-Z. Chang, H. Li, K. He, D. Zhang, M. Singh, X.-C. Ma, N. Samarth, M. Xie, Q.-K. Xue, and M. H. W. Chan, Phys. Rev. B 85, 045415 (2012).
22 T. H. Hsieh and L. Fu, Phys. Rev. Lett. 108, 107005 (2012).
23 J. Shen, Y. Xie, and J. J. Cha, Nano Lett. 15, 3827 (2015).
24 M. Novak, S. Sasaki, M. Kriener, K. Segawa, and Y. Ando, Phys. Rev. B 88, 140502 (2013).
25 S. Sasaki and Y. Ando, Cryst. Growth Des. 15, 2748 (2015).
26 T. Sato, Y. Tanaka, K. Nakayama, S. Souma, T. Takahashi, S. Sasaki, Z. Ren, A. A. Taskin, K. Segawa, and Y. Ando, Phys. Rev. Lett. 110, 206804 (2013).
27 N. Haldolaarachchige, Q. Gibson, W. Xie, M. B. Nielsen, S. Kushwaha, and R. J. Cava, Phys. Rev. B 93, 024520 (2016).
28 R. D. Zhong, J. A. Schneeloch, X. Y. Shi, Z. J. Xu, C. Zhang, J. M. Tranquada, Q. Li, and G. D. Gu, Phys. Rev. B 88, 020505 (2013).
29 S. Sasaki, Z. Ren, A. A. Taskin, K. Segawa, L. Fu, and Y. Ando, Phys. Rev. Lett. 109, 217004 (2012).
30 R. P. Huebener and D. E. Gallus, Phys. Lett. A 44, 443 (1973).
31 D. E. Chimenti, H. L. Watson, and R. P. Huebener, J. Low Temp. Phys. 23, 303 (1976).
32 A. Bezryadin, C. N. Lau, and M. Tinkham, Nature 404, 971 (2000).
33 A. Bezryadin, J. Phys.: Condens. Matter 20, 043202 (2008).
34 M. Tinkham, J. U. Free, C. N. Lau, and N. Markovic, Phys. Rev. B 68, 134515 (2003).
35 G. R. Boogaard, A. H. Verbruggen, W. Belzig, and T. M. Klapwijk, Phys. Rev. B 69, 220503(R) (2004).
36 A. T. Bollinger, A. Rogachev, M. Remeika, and A. Bezryadin, Phys. Rev. B 69, 180503(R) (2004).
37 M. Tian, N. Kumar, M. H. W. Chan, and T. E. Mallouk, Phys. Rev. B 78, 045417 (2008).
38 C. Maeda, S. Katsube, and G.-q. Zheng, J. Phys. Soc. Jpn. 86, 024702 (2017).
39 S. Atherton, B. Steele, and S. Sasaki, Crystals 7, 78 (2017).
40 P. W. Anderson, J. Phys. Chem. Solids 11, 26 (1959).
41 S. Bose, P. Raychaudhuri, R. Banerjee, P. Vasa, and P. Ayyub, Phys. Rev. Lett. 95, 147003 (2005).