# Potential Fu–Kane Topological Superconductor Island in $Bi_2Te_3/VSi_x/Si$ Nanostructure

Dang Liu[1], Pei-Yuan Cai[2,3], Yisheng Gu[1], Qiaoyan Yu[1], Shasha Xue[1], Ruijun Xi[1], Xingsen Chen[1], Jice Sun[1], Xian Du[1], Yi Zhang[1], Xuhui Ning[1], Tingwen Miao[1], Pengyu Hu[1], Hao Yang[1], Dandan Guan[1], Xiaoxue Liu[1], Liang Liu[1], Yaoyi Li[1], Shiyong Wang[1], Canhua Liu[1], Yi Zhou[2,3], Hao Zheng[1*], and Jinfeng Jia[1,4,5*]

[1]*Tsung-Dao Lee Institute, Key Laboratory of Artificial Structures and Quantum Control (Ministry of Education), School of Physics and Astronomy, Shanghai Jiao Tong University, Shanghai 200240, China*
[2]*Institute of Physics, Chinese Academy of Sciences, Beijing 100190, China*
[3]*University of Chinese Academy of Sciences, Beijing 100190, China*
[4]*Department of Physics, Southern University of Science and Technology, Shenzhen 518055, China*
[5]*Quantum Science Center of Guangdong-Hong Kong-Macao Greater Bay Area (Guangdong), Shenzhen 518045, China*

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Topological superconductor islands are thought to be the building blocks of topological quantum bits. We produced single-crystalline $VSi_x$ islands with well-defined side facets and island size more than 200 nm using molecular beam epitaxy on Si substrate heated to 950 °C throughout the growth process. By means of scanning tunneling spectroscopy, we revealed dynamical Coulomb blockade and superconductivity on isolated islands and on islands being connected by superconducting wetting layer respectively. $Bi_2Te_3$ films were further deposited on $VSi_x$ islands. Robust and homogenous proximity effect induced superconductivity was observed on various facets of the $Bi_2Te_3/VSi_x$ hetero-nanostructure. Furthermore, our high-resolution spectroscopy identified Bosonic mode excitations on the topological superconductor islands. These results may establish a playground for the vortex Majorana islands.

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*1. Introduction.* Topological superconductors are exotic topological materials, having fully gaped bulk states and gapless boundary excitations in the form of Majorana quasiparticles.[1–7] Majorana quasiparticles which obey non-Abelian statistics are promising to realize fault-tolerant topological quantum computing.[8,9] Topological superconductors thus have attracted lots of attention from theoretical and applied researchers.[10–14]

Theoretical study revealed that an isolated island containing for Majorana zero modes, i.e., so-called Majorana island,[15–17] can serve as a basic unit of topological superconducting qubit.[16,18] Moreover, Majorana island is also a suitable platform to study Majorana physics. Most of experimental studies are based on semiconductor nanowire covered with epitaxial superconductor. In InAs/Al system, scientists found exponential protection of Majorana modes in the form of a suppression of energy splitting with increasing nanowire length.[15] Signature of electron teleportation was found in InAs–Al Majorana island embedded in an Aharonov–Bohm interferometer.[19] However, the study of Majorana island based on another promising system which is the Fu–Kane model predicted topological insulator/superconductor (TI/SC) heterostructure,[1,2,20–29] is still lacking.

The first obstacle to hinder the fabrication of TI/SC Majorana island is probably due to the lacking of suitable SC island. Pb is a widely studied s-wave superconductor, with a $T_C$ about 7.2 K. Pb islands can be readily prepared by molecular beam epitaxy (MBE).[30–34] However, growth temperature of Pb is relatively low due to its low melting point (327 °C for bulk Pb).[35,36] The growth temperature of the typical TI $Bi_2Te_3$ is about 260 °C. In such temperature, Pb island becomes mobile and fragile. Vanadium (V) is a type-II superconductor with a $T_C \sim 5.4$ K.[37] Above all, V has a melting temperature as high as 1929 °C,[38] so the thermodynamic properties of V island should be very stable.

In this work, we use MBE to fabricate $Bi_2Te_3/VSi_x$ topological superconducting islands, study its electronic properties by ultra-low temperature scanning tunneling microscopy/spectroscopy (STM/S). We proved it to be an ideal platform of vortex Majorana island.

*2. Results and Discussion.* Firstly, V was deposited on Si (111) with the temperature of substrate kept at 850 °C–

*Corresponding author. Email: haozheng1@sjtu.edu.cn; jfjia@sjtu.edu.cn
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1000 °C. Under such high temperature, we believe the $VSi_x$ compound has formed. Figure 1(a) shows a typical STM topography image of the polyhedral shaped $VSi_x$ islands. Moreover, we can still find Si (111) 7×7 in the area between islands [Fig. 1(b)] at relatively low coverage. It proves that the $VSi_x$ islands are isolated from each other. In such situation, our $dI/dV$ spectrum in Fig. 1(c) shows only a small dip around zero bias without coherence peak. The zero bias conductance (dip bottom) does not reach zero. As we know, when the temperature in a tunneling junction is so low that the thermal energy $k_BT$ is comparable or less than charging energy $E_C = e^2/2C_J$ ($e$ is the elementary charge, $C_J$ is capacitance of tunnel junction), the dynamical Coulomb blockade (DCB) may be established.[39–41] In DCB regime, suppression of local density of states (LDOS) at small energy is due to interaction of electron with electromagnetic environment. We believe the dip in our $dI/dV$ spectrum on the isolated $VSi_x$ island is induced by DCB and use $P(E)$ theory of DCB[40–42] to understand our data. In this theory, tunneling current can be written as $I(V) = e[\Gamma_{\text{isl}\to\text{tip}}(V) - \Gamma_{\text{tip}\to\text{isl}}(V)]$, where $\Gamma_{\text{isl}\to\text{tip}}(V)$ is inelastic tunneling rates from island to tip,

$$\Gamma_{\text{isl}\to\text{tip}}(V) = \frac{1}{e^2 R_T}\int_{-\infty}^{\infty} dE \frac{EP(eV+E)}{\exp\left(\frac{E}{k_BT}\right)-1}, \quad (1)$$

and $\Gamma_{\text{tip}\to\text{isl}}(V) = \Gamma_{\text{isl}\to\text{tip}}(-V)$. $R_T$ is tunneling resistance, $P(E)$ is the probability for an electron to emit the energy $E$ into the electromagnetic environment.[42] Calculation of $P(E)$ depends on total impedance $Z(\omega) = [i\omega C_{\text{isl}} + 1/R_{\text{isl}}]^{-1}$, where $C_{\text{isl}}$ and $R_{\text{isl}}$ are the effective capacitance and resistance of $VSi_x$ island (detailed calculation can be seen in Supplementary Material).

In Fig. 1(c), we indeed can fit our spectrum by the simulation based on DCB theory, and thus can deduce the resistance and capacitance of our $VSi_x$ island as 2.56 kΩ and 5.9 aF respectively. Next, we increase the coverage and find the emergence of amorphous wetting layer between $VSi_x$ islands [Figs. 1(d) and 1(e)]. Our $dI/dV$ spectra on and off $VSi_x$ islands are displayed in Fig. 1(f). We now can successfully observe superconducting gap with gap size at ∼ 0.34 meV and clear coherent peaks both on the island and on substrate. Apparently, superconductivity is established on our sample. Transition from DCB to superconducting regime can be understood by the change of capacitance of samples. When the coverage is low and islands are isolated, the capacitance is small leading to a big charging energy, then DCB might happen. For high coverage situation, islands are connected and have higher capacitance, so superconductivity will not be affected and can be seen in our STS experiments. Both element V and compound $V_3Si$ are SCs. The superconducting gap sizes of V and $V_3Si$ are 0.75 meV[43] and 1.36 meV,[44] respectively. The gap size of our island appears to be much smaller than these two values.

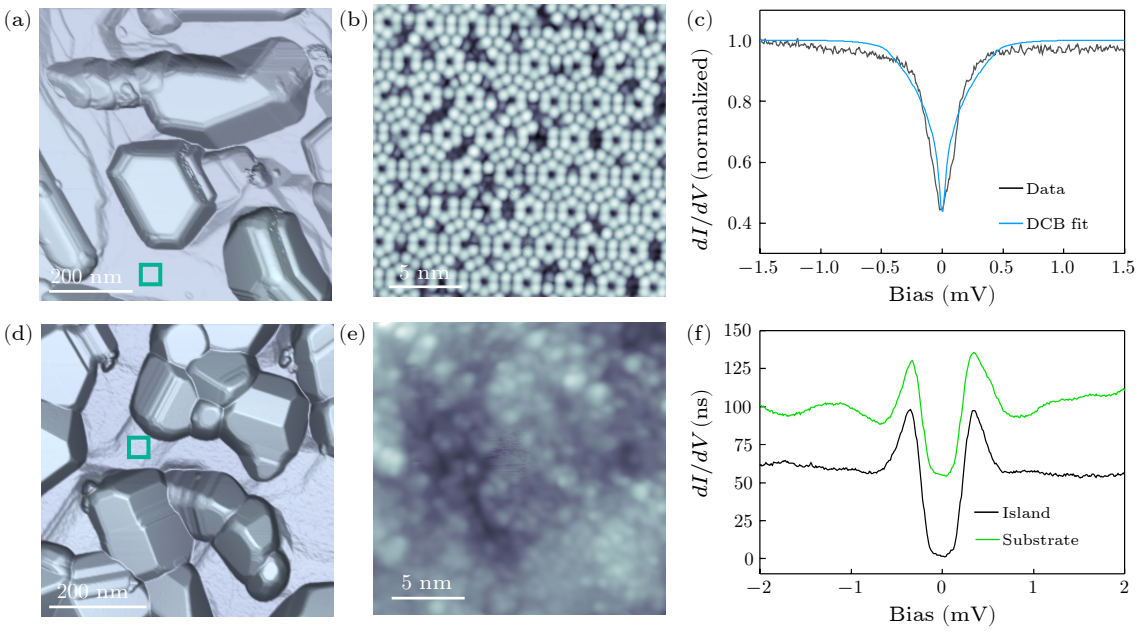


**Fig. 1.** Dynamical coulomb blockade and superconductivity on $VSi_x$ islands with different coverages. (a) STM image (1 V, 0.1 nA, 700 × 700 nm$^2$) of VSix islands which were grown with substrate at 950 °C for 100 minutes. Heights of islands are 30–50 nm. (b) STM image showing the Si (111) 7 × 7 reconstruction surface in-between the VSix islands. The image was taken at the position indicated by the square (not to scale) in panel (a). (c) Black line: normalized $dI/dV$ spectrum taken on one island. Blue line: Fittings by using DCB theory. (d) STM image (600 × 600 nm$^2$) depicting a sample grown at 850 °C for 120 minutes. Heights of islands are around 40 nm. (e) STM image showing amorphous wetting layer, which was taken at the squire (not to scale) in panel (d). (f) Typical U-shaped superconducting gaps appeared both on and off island (the spectra are shifted by 50 nS for clarity). All date were acquired at 20 mK.

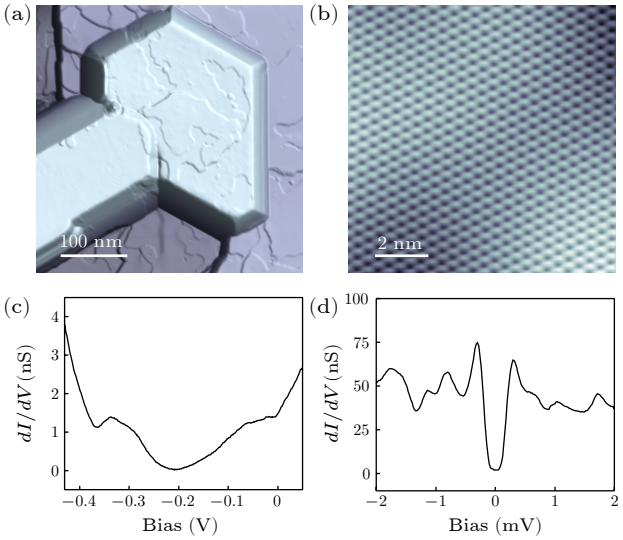


**Fig. 2.** Characterization of $Bi_2Te_3$ grown on $VSi_x$ island. (a) STM image (1 V, 0.05 nA) of a $Bi_2Te_3/VSi_x$ island. Heights of islands are $\sim$ 45 nm. (b) Atomically resolved image (0.5 V, 1 nA) of the $Bi_2Te_3$ lattice. (c) $dI/dV$ spectrum (4.8 K) of $Bi_2Te_3$ /$VSi_x$ island for a wide range of energies. (d) $dI/dV$ spectrum (20 mK) exhibiting a clear proximity-induced superconducting gap.

In order to understand this discrepancy, we pay attention to the crystalline structure of the island. Figure S1 in Supplementary Material shows a typical island with a hexagonal top surface and six side facets. We obtain atomic resolution STM images on each facet. Lattice constants in the atomic image are measured in different facets and different islands. However, none of them match the lattice constant of V or $V_3Si$. Formation of vanadium silicide such as $VSi_2$, was found when V was deposited on Si (111) at room temperature with post annealing up to 1000 K.[45–50] Thus, the V–Si compounds other than $V_3Si$ may account for the sample. Another possible explanation of small SC gaps is the size effect in nanoscale.[51–54] When a superconductor is reaching its characteristic length scales, such as the London penetration depth or the coherence length, changes on superconductivity might happen.[55] For examples, the gap size of nanoscale Pb islands decreased with decreasing of island size and height,[56] which was also observed in Nb nanoparticles.[55] However, variation of gap value compared with V or $V_3Si$ is big, considering the lateral size of $VSi_x$ island. Therefore, it is likely to be a new V–Si compound superconductor.

After successfully fabricating SC islands, we grow thin films of TI $Bi_2Te_3$ on these $VSi_x$ islands. In our previous research, high-quality $Bi_2Te_3$ thin films grown on bulk crystal $NbSe_2$, and evidence of the existence of Majorana zero mode was clearly detected.[7] The similar growth conditions were adopted here. After deposition, we notice that overall morphology of island remain unchanged [Fig. 2(a)]. It proves that our 900 °C grown $VSi_x$ islands are robust against the temperature of 260 °C, e.g. the typical growth temperature of $Bi_2Te_3$. We emphases that the $VSi_x$/Si sample is actually a suitable SC island substrate for further MBE growth, which usually takes place at below 500 °C. Figure 2(b) represents the STM image on top of an island. It revealed that the atoms were arranged in a hexagonal lattice with a lattice constant of 0.44 nm, consistent with reported value for $Bi_2Te_3$.[57] Our $dI/dV$ spectra as shown in Fig. 2(c) exhibited that TI characteristics of the $Bi_2Te_3/VSi_x$ island. Based on the spectra, we obtained that valence band top and conduction band bottom are located at $-0.34$ eV and $-0.08$ eV, respectively, yielding a bandgap of 0.26 eV. In the study of epitaxial growth of $Bi_2Te_3$ on $NbSe_2$, one found $Bi_2Te_3$ bandgap reached 0.25 eV if the film thickness exceeds 3 quintuple layers (QL) in previous study,[1] we thus know that our TI films grown on islands are thicker than 3QL, in which the topological surface state is established. We then pay attention to the superconductivity in our islands. Our small energy scale $dI/dV$ spectra [Fig. 2(d)] showed a typical superconducting energy gap with a gap size of 0.3 meV which is slightly smaller than bare $VSi_x$ islands.

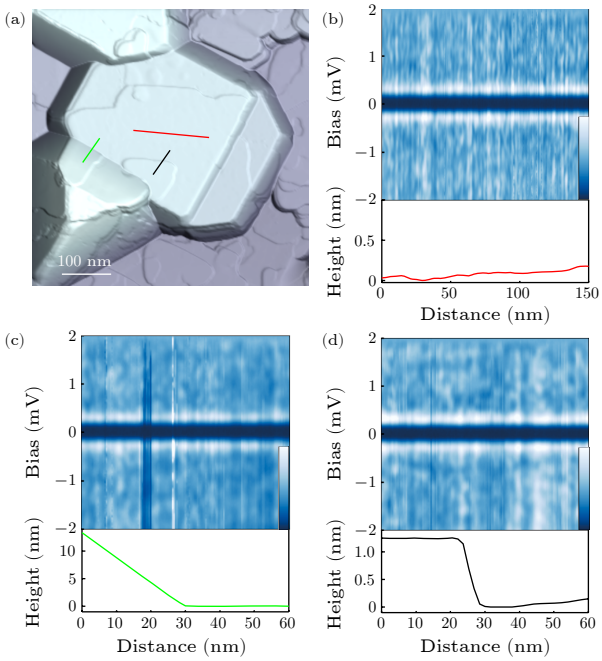


**Fig. 3.** Robust and uniform superconductivity of $VSi_x/Bi_2Te_3$ island. (a) Morphology of $Bi_2Te_3/VSi_x$ islands. (b)–(d) Spatially resolved $dI/dV$ spectra (20 mK). which were acquired along the red, green and black lines in (a), respectively. The superconducting gaps are robust and uniform despite the different facets.

The shape of $VSi_x$ islands exhibits a multiple-facets three-dimensional configuration, providing a platform to study SC proximity effect in places with different geometry and physical environments. We investigated the distribution of superconductivity in different regions on an island. In Fig. 3, it can be seen that $Bi_2Te_3$ on $VSi_x$ island can be divided into three different regions: flat terrace on top surface, stepped terrace on top surface and terrace on side

facet. We measured the spatial distribution of SC gaps in these three areas, and results are given in Figs. 3(b)–3(d). In Fig. 3(b), superconductivity appears very uniform on flat $Bi_2Te_3$ terrace which shows good quality of the sample. In Fig. 3(d), we measured $dI/dV$ spectra across a $Bi_2Te_3$ step, but did not observe obviously change of SC gap. It indicates that $Bi_2Te_3$ grown on $VSi_x$ has a long mean free path, which is also an evidence for good quality of TI films. Moreover, we conducted position dependent $dI/dV$ measurements on adjacent facets. As displayed in Fig. 3(c), superconductivity still looks robust and uniform despite that the two terraces are in different geometries. The uniform and robust proximity-induced superconductivity in our $Bi_2Te_3/VSi_x$ sample makes it easier to fabricate high quality Majorana island devices in the future.

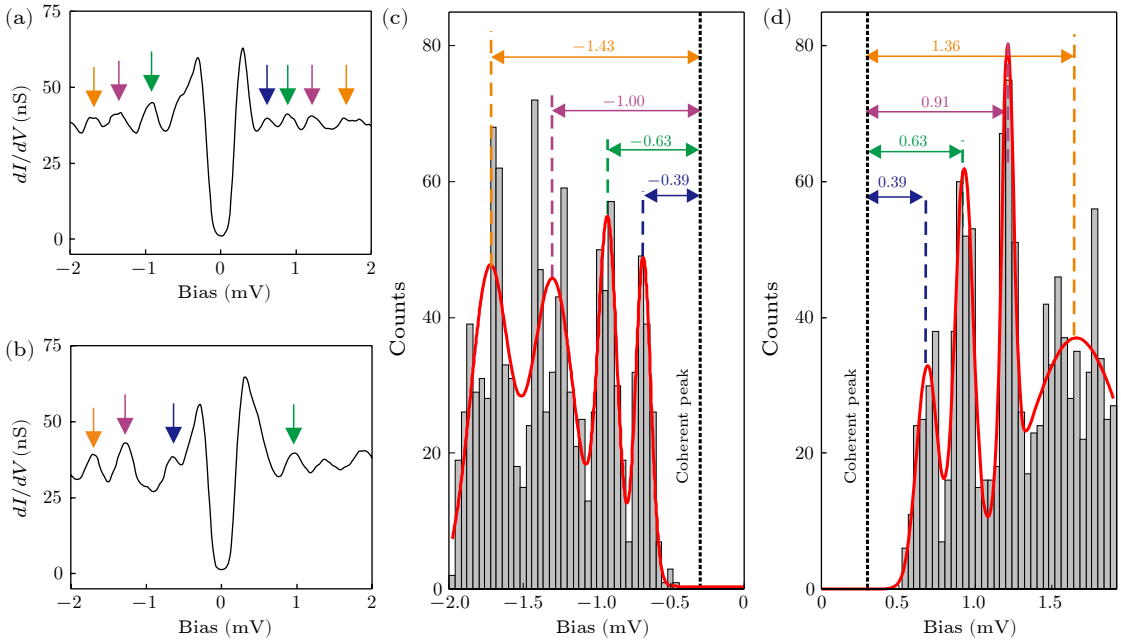


**Fig. 4.** Statistical analysis of satellite peaks in superconducting spectra on $Bi_2Te_3/VSi_x$ island. (a) and (b) two typical $dI/dV$ spectra of $Bi_2Te_3$ on $VSi_x$. The arrows indicate different energy satellite peaks in addition to the superconducting coherent peaks. (c) and (d) Histogram of peak energy distribution of 365 $dI/dV$ spectra. Red lines are Gaussian fittings. Black dashed lines represent positions of coherent peaks.

Beside the SC on our sample, we also find exotic satellite peaks outside the coherent peaks in the $dI/dV$ spectra. Figures 4(a) and 4(b) represent two typical $dI/dV$ curves, where several satellite peaks and dip-hump features can be clearly resolved. We conducted statistical analysis of 365 $dI/dV$ curves obtained in one $Bi_2Te_3/VSi_x$ island. The results are displayed in Figs. 4(c) and 4(d). From the distribution of peaks' energy in histogram, one can find that some energy scales have much more counts. Fitted by Gaussian function, we can get energy values of these peaks, defined by separation between nearest coherent peak. As for the first three pairs of peaks, energy separation seems to be a constant, around 0.3 meV. Therefore, energy of the first three pairs of peaks can be interpreted as $\Omega_n = n \times \Omega_1 = n \times 0.3\,\text{meV}$ ($\Omega_n = E_n - \Delta$ with $E_n$ the energy of the $n$th peak from $E_F$), which indicates these peaks may have same origin. This kind of feature resembles bosonic modes discovered on both BCS superconductors and materials show unconventional superconductivity.[56,58,59] Since phonon modes of $Bi_2Te_3$ thin films are found to be a few meV to tens of meV in Raman experiments,[60] we may rule out the phonons as origin of these peaks. Also, it is not likely to ascribe it to magnetic excitation, because $Bi_2Te_3$ is nonmagnetic. Moreover, we note that the $dI/dV$ spectrum on bare $VSi_x$ island [Fig. 1(f)] is flat outside the coherent peak, and satellite peaks only appear after deposition of TI. Therefore the interface effect may play an important role.[61] Bosonic mode associated with proximity induced superconductivity might inspire studies on collective modes in superconductors.

*3. Methods.* The experiment was performed using a commercial Dilution-refrigerator based UHV scanning tunneling microscopy system USM-1600 (Unisoku), equipped with a molecular beam epitaxy chamber and a vector magnetic field ($H_x$:2 T, $H_y$:2 T, $H_z$:9 T). Boron-doped Si (111) was degassed and flashed entail showing $7 \times 7$ reconstructions. V (99.5%) was deposited on Si by E-beam evaporator. Bi (99.999%) and Te (99.999%) were evaporated from standard Knudsen cells at a substrate temperature of $\sim$ 260 °C. The ratio of Bi:Te was about 1 : 10. After growth, samples were immediately transferred to STM. The tip used for STM is a chemically etched W tip calibrated on Ag. The STM measurements in this article

were carried out at 4.8 K and 20 mK.

*4. Conclusion.* We successfully prepared single crystalline $Bi_2Te_3/VSi_x$ islands, which could be a new topological superconducting island heterostructure fulfilling the requirement of Fu–Kane model. The high thermal stability and robust superconductivity makes it as a promising platform for further study of Majorana physics and topological quantum computing.

*Associated Content.* The Supporting Information is attached as a separate file. Supporting Information: STM measurements of other samples and regions, theoretical calculation details and data analysis method (DOC).

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