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研究課題名（和文） Microwave Spectroscopy of Hybrid Topological Systems

研究課題名（英文） Microwave Spectroscopy of Hybrid Topological Systems

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研究成果の概要（和文）： InAsナノワイアとBiナノワイアに超伝導体金属を蒸着しジョセフソン接合を作製しその特性を調べた。作製に際しては、真空を破ることなく接合を形成することにより、エッチングによるダメージを防ぐことができた。InAsナノワイアにおいては超伝導体で作製したマイクロ波回路共振器と結合させることに成功し、接合に形成されたアンドレーエフ束縛状態のエネルギースペクトルを位相の関数として測定した。その結果、スピン軌道相互作用と閉じ込め効果がスペクトルに影響を与えることが分かった。

研究成果の学術的意義や社会的意義

The cavity coupled spectroscopy method developed in this study can be flexible applied to any Josephson system and can thus be of great value to the study of other Andreev bound states, not just in exotic systems but also fundamental properties of superconducting circuits for quantum computing.

研究成果の概要（英文）： We fabricate and study Josephson junctions in both InAs and bismuth nanowires with deposition of superconducting contacts performed in-situ within the growth system. In both systems Josephson junctions are formed through the shadowing of overlapping nanowires avoiding the need for etching in device processing and protecting the nanowire surface from unnecessary damage. We couple single InAs nanowire Josephson junctions to superconducting coplanar microwave cavities and perform the dispersive readout of single Andreev bound states. Andreev bound state spectroscopy reveals not just the dispersion of single states in phase but also the presence of spin-split Andreev states through the interplay of spin-orbit interaction and confinement.

研究分野： Condensed Matter Physics

キーワード： Andreev Bound state　Josephson junction　Nanowire　Resonator　Topological　Majorana

1.　研究開始当初の背景 (background at start of research)

Andreev bound states (henceforth ABSs) are ubiquitous in microscopic theories of Josephson junctions (henceforth JJs), and carry the supercurrent in short junctions. They appear as pairs of states within the superconducting gap at energies $\pm\varepsilon_A$ and have a dispersion in energy as a function of superconducting phase difference (φ) across the JJ, Fig. 1. Despite the fundamental nature of these states to the properties of JJs the detection of single ABSs in devices was only first demonstrated in 2010. Spectroscopy of ABSs can be an important tool to study hybrid JJs producing a 'fingerprint' of the superconducting proximity effect that gives rise to more typically measured collective properties such as the current phase relationship. Of particular current interest is the use of spectroscopic measurements to probe topological superconducting states. In seminal work in 2008 Fu and Kane proposed that the proximity effect in a hybrid topological insulator – *s*-wave superconductor device can lead to an effective spinless *p*-wave superconducting state [Fu and Kane, Phys. Rev. Lett. 100, 0964407 (2008)]. Under special conditions such a state can host zero energy ABS which are the so-called Majorana modes. Combined with techniques to gap out topological edge states localized Majorana Fermions maybe realized which have application for quantum computation. Similar proposals based on 1-dimensional semiconductor nanowire devices predict accessible Majorana Fermion states in an applied magnetic field [R.M. Lutchyn *et al.*, PRL 105, 077001 (2010)]. In recent years considerable progress has been made to elucidate the presence of Majorana Fermions in these systems with a focus on tunneling spectroscopy revealing zero energy states in which it has been found to be difficult to distinguish trivial and topological states.

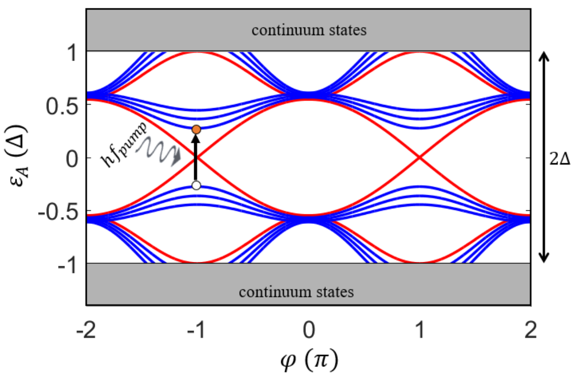

Fig. 1. (a) Illustration of ABSs energies ε_A for both trivial (blue) and topological (red) modes. The arrow indicates an example excitation of a trivial state with a microwave photon. The excitation frequency is $f_A = 2\varepsilon_A/h$.

２．研究の目的 (Purpose of research)

In this project we aim to probe the dispersion of ABSs in Josephson weak links through coupling to a microwave cavity. Spectroscopic measurements of ABSs can provide detailed information about the presence of topologically protected crossings which are the hallmark of strongly hybridized Majorana Fermions or Majorana modes. We proposed to use coplanar microwave resonators coupled to a flux biased JJ to perform dispersive readout of the phase dispersion of ABSs. As the target topological JJs, we study InAs nanowires with axial magnetic fields and bismuth nanowires which are predicted to exhibit the properties of higher order topological insulators.

３．研究の方法 (Research method)

We perform spectroscopy of the ABSs in a JJ using a high Q-factor (internal Q~400,000) superconducting coplanar waveguide resonator as a sensitive detector. A loop containing the test JJ allows a flux bias and inductively couples the ABSs to a quarter wavelength resonator. At low powers the state of the test JJ will cause dispersive shifts in the cavity response. A second pump tone applied to gates or a flux bias line will drive transitions in the ABS spectrum allowing detection of allowed transition energies in the cavity response. In the role of the test JJ, we explore primarily two systems. The first being InAs nanowires which are an extensively studied platform for engineering topological superconducting states. Second, we explore the fabrication of bismuth nanowire JJs which are predicted to exhibit properties of a higher order topological insulator [Schindler *et al.*, Nat. Phys. 14, 918 (2018)]. In both cases we aim to develop fabrication methods to produce highly transparent JJs through *in-situ* deposition of superconducting contacts with device geometry achieved through shadowing of overlapping nanowires.

４．研究成果 (research results)

Research results are summarized into the three sections which follow: The fabrication and characterization of JJ devices based on InAs nanowires (i), bismuth nanowires (ii) and finally the development of devices for spectroscopic measurements of ABSs (iii).

(i) InAs nanowire JJs – InAs Nanowires were grown in the lab of our collaborator (Prof. Thomas Schäper, Jülich, Germany) with devices fabricated in our laboratory in RIKEN. Through development of an *in-situ* JJ fabrication method we form JJs with high transparency aluminium contacts. The site selected growth of nanowires allows the fabrication of crossing pairs of wires such that the upper wire may shadow the lower during *in-situ* deposition of aluminium within the MBE growth chamber. We have demonstrated that the resulting interfaces are of excellent quality resulting is highly transparent JJs with hard superconducting gaps [Ref. 1]. Such high transparency JJs are ideal for the ABSs spectroscopy discussed later. In addition to aluminium contacts, we demonstrate the technique maybe extended to other superconductors such as niobium [Ref. 2]. In addition, we have studied n-type InAs nanowires through Tellerium doping to be used as a possible shunting JJ in more complex superconducting circuits [Ref. 3] such as asymmetric SQUIDs.

(ii) Bismuth nanowire JJs - We developed a *in-situ* JJ fabrication method for the production of bismuth

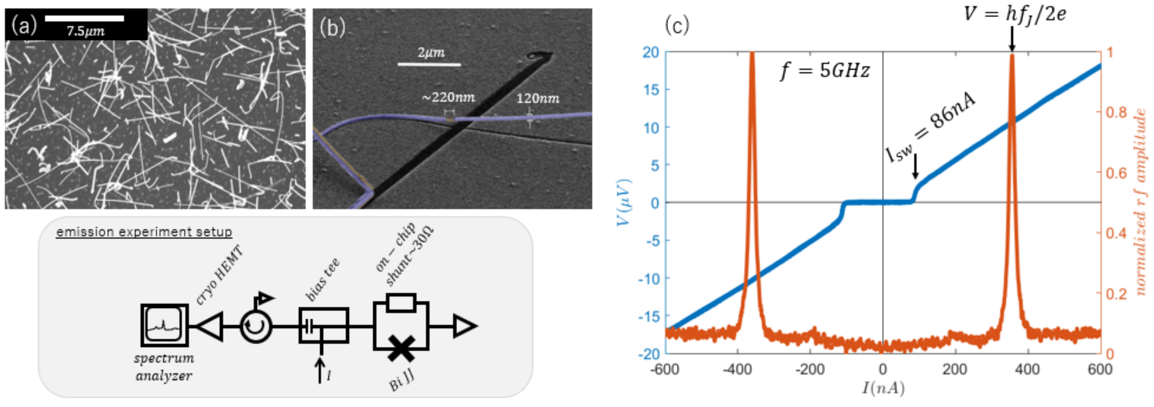

Fig. 2. (a) Example scanning electron microscope image of the as-grown Bi nanowires showing many crossing nanowires. (b) Example of a shadow deposited JJ with an Aluminium film. The shadow region is clearly visible on the growth substrate. (c) Example measurement of a bismuth nanowire JJ with $I_{sw} \sim 86\, nA$ switching current. A successful JJ is confirmed through observation of the ac-Josephson effect, detecting the Josephson emission from the JJ at the Josephson frequency $f_J = 2eV/h$. The Josephson emission here is detected using the measurement scheme shown with the spectrum analyzer operating at 5GHz and a bandwidth of 10MHz.

nanowire Josephson weak links. Nanowires are grown through electron beam deposition of bismuth onto a rough surface of sputtered or electron beam deposited vanadium which provides nucleation centers. Both vanadium and bismuth deposition are performed within the same chamber with control of substrate temperature allowing modification of resulting nanowire density and distribution of wire diameters. Following the nanowire growth, we deposit aluminium superconductor while cooling the substrate to liquid nitrogen temperatures. The chance crossing of nanowires during growth allows the realization of shadowed JJs, Fig. 2 (a) and (b). Individual nanowires may then be transferred to a device substrate and contacted for study of the JJ properties. The *in-situ* aluminium deposition avoids the need to later strip bismuth oxide to achieve transparent contacts and as such can preserve crystal structure and wire surface. The limitation of damage to the wire is of value in the study of potential surface states of the system. We successfully form JJs and study both dc transport and the ac-Josephson effect, Fig. 2 (c). Studies reveal JJs dominated by diffusive transport but we were unable to detect the presence of topologically protected one-dimensional modes that have been reported to exist along so-called ‘hinges’ between crystal facets (a report on this study is currently under submission) [Ref. 4]. We speculate that the ‘hinge’ states are masked by the large diffusive contribution to the supercurrent from the bulk and that in future this can be mitigated by producing longer JJs on thinner diameter nanowires through maximizing the distribution of the nanowire diameters produced during growth.

(iii) Spectroscopy of ABSs through microwave cavity coupling – Using the shadow formed high transparency InAs JJs in (i) we demonstrate the dispersive readout of single ABSs using a microwave cavity. An example device layout is shown in Fig. 3(a) with a multiple quarter wavelength coplanar waveguide resonators readout using a single transmission line. Nanowires from the growth substrate are positioned using a micromanipulator onto pre-patterned gate pads and contacted with a sputtered niobium titanium loop to form an rf-SQUID circuit, Fig. 3(c). The JJ phase is controlled through application of a current to a nearby flux biasing line. A second microwave tone (pump tone f_{pump}) is applied through the gate line allowing excitations between ABS in the JJ. The device maybe probed through monitoring the cavity transmission at the probe frequency f_{probe}, which is typically set at the bare cavity resonance $f_0 \sim 5.666$ GHz. The coupling between cavity and ABSs causes a dispersive shift of the cavity resonance frequency [Ref. 5]. Tuning of the JJ gate causes ABSs to shift in energy within the gap resulting in resonance frequency shifts that depend on the detuning of ABS transition

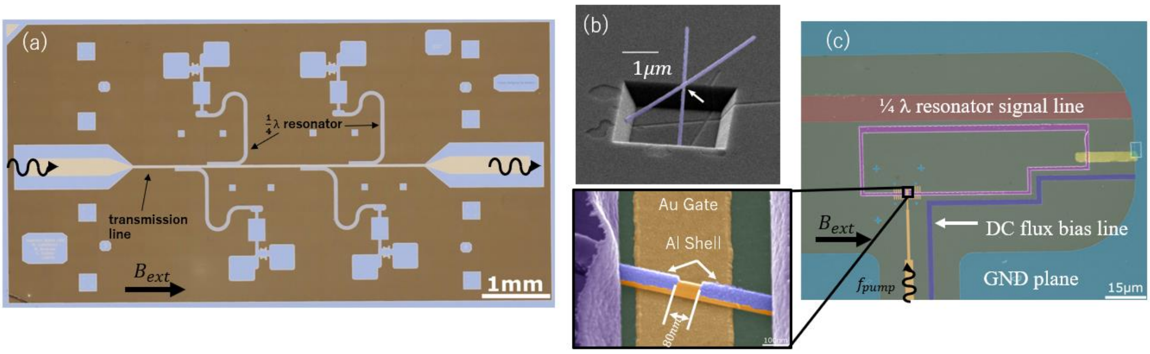

Fig. 3. (a) Optical image of a TiN resonator consisting of a transmission line with four quarter wavelength resonators. (b) Scanning electron microscope image of site selected grown InAs nanowires on the growth substrate where crossing of wire pairs forms a shadowed JJ. (c) rf-SQUID circuit fabricated at the end of a quarter wavelength resonator.

from the bare cavity frequency, Fig. 4 (a). The application of a second microwave tone to the JJ can allow the mapping of the phase dispersion of the ABS as shown in Fig. 4 (c). To facilitate the application of a magnetic field to drive the InAs nanowire into the topological regime we construct a homemade compact superconducting coil which is enclosed within magnetic shielding to reduce flux noise at the device. We design resonators based on thin films of TiN and Niobium with the inclusion of flux traps that can maintain resonances with acceptable internal Q-factors up to fields of several Tesla. Future work will further probe the system from trivial states at low fields into high magnetic field regimes where the topological transition is predicted.

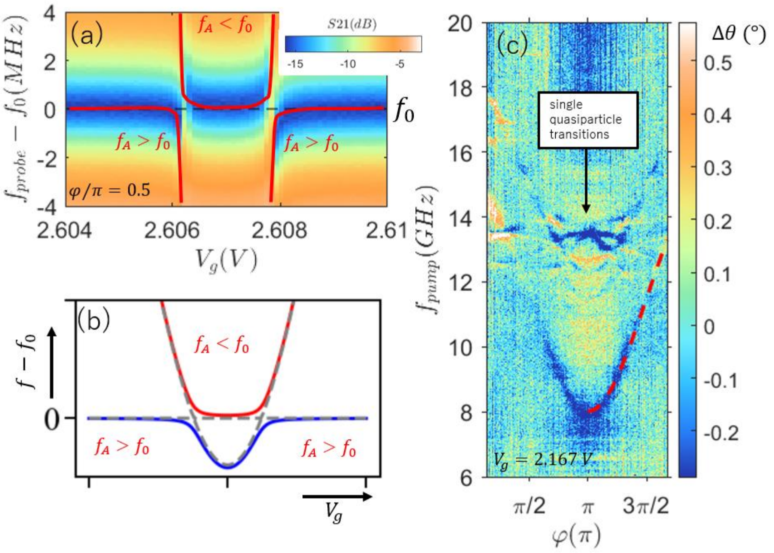

Fig. 4. (a) Single tone response showing the dispersive shift of the cavity resonance as successive ABSs are tuned to and through zero detuning with the cavity frequency. (b) Illustration of the cavity shift as the transition frequency f_A for excitation of the ABS is tuned rough the bare cavity frequency f_0. The sign of the cavity frequency shift reverses as the detuning is tuned through zero. (c) Two tone spectroscopy measurement showing the dispersion of several single ABSs. Fine structure about a phase difference of $\varphi = \pi$ indicates single quasi-particle transitions between ABSs in a long JJ. The red dashed line indicates a qualitative fit to the expected dispersion of an ABS in a long JJ.

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4. “Bismuth nanowires with *in-situ* shadow deposited Josephson junctions”, H. Wang, R. S. Deacon, K. Ishibashi. (*submitted*)
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５．主な発表論文等

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２．論文標題 Hard-Gap Spectroscopy in a Self-Defined Mesoscopic InAs/Al Nanowire Josephson Junction	５．発行年 2020年
３．雑誌名 PHYSICAL REVIEW APPLIED	６．最初と最後の頁 54019
掲載論文のDOI（デジタルオブジェクト識別子） 10.1103/PhysRevApplied.14.054019	査読の有無 有
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１．著者名 Pujitha Perla, H. Aruni Fonseka, Patrick Zellekens, Russell Deacon, Yisong Han, Jonas Kolzer, Timm Morstedt, Benjamin Bennemann, Abbas Espiari, Koji Ishibashi, Detlev Grutzmacher, Ana M. Sanchez, Mihail Ion Lepsa and Thomas Schapers	４．巻 3
２．論文標題 Fully in situ Nb/InAs-nanowire Josephson junctions by selective-area growth and shadow evaporation	５．発行年 2021年
３．雑誌名 Nanoscale Advances	６．最初と最後の頁 1413-1421
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２．論文標題 Te-doping selective-area grown InAs nanowires for superconducting hybrid devices	５．発行年 2022年
３．雑誌名 Physical Review Materials	６．最初と最後の頁 24602
掲載論文のDOI（デジタルオブジェクト識別子） 10.1103/PhysRevMaterials.6.024602	査読の有無 有
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１．発表者名 R. S. Deacon
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2019年

１．発表者名
R. S. Deacon

２．発表標題
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2019年

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P. Zellekens

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2022年

１．発表者名
P. Zellekens

２．発表標題
Microwave spectroscopy of Andreev states in InAs nanowire-based hybrid junctions

３．学会等名
NANOWIRE WEEK 2022, Chamonix, France.（国際学会）

４．発表年
2022年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

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6．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考

7．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

8．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関			
ドイツ	Prof. Thomas Schaper	Peter Grunberg Institut (PGI-9)	Forschungszentrum Julich	