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Review of Superconducting Nanostrip Photon Detectors using Various Superconductors

Hiroyuki SHIBATA[†a)], ***Member***

SUMMARY One of the highest performing single-photon detectors in the visible and near-infrared regions is the superconducting nanostrip photon detector (SNSPD or SSPD), which usually uses NbN or NbTiN as the superconductor. Using other superconductors may significantly improve, for example, the operating temperature and count rate characteristics. This paper briefly reviews the current state of the potential, characteristics, thin film growth, and nanofabrication process of SNSPD using various superconductors.
key words: *single-photon detector, SNSPD, SSPD, superconductor*

1. Introduction

In the last 20 years of development, superconducting nanostrip photon detector (SNSPD or SSPD)[*] has significantly improved its performance, which is used in various fields such as quantum key distribution, photonic quantum computer, quantum optics, satellite laser ranging, space laser optical communication, and fluorescence lifetime measurement [1]–[5]. SNSPD has excellent performance: very high system detection efficiency (SDE > 90%), negligible dark count rate (DCR < 0.01 Hz), high count rate (CR > 100 MHz), and low jitter (< 20 ps) [3]–[15]. Further improvements, including a long wavelength detection, broadband detection, large detection area, photon-number detection, multi-element, high-operation temperature, and simultaneous achievement of these characteristics, are in progress to expand its application field [3]–[5]. Selecting the superconductors is one of the most important factor in the development.

In the diffusion-based hotspot model, the detection limit energy is given by $hc/\lambda \sim N_0\Delta^2 wd\sqrt{\pi D\tau_{\rm th}}(1-I_{\rm bias}/I_{\rm c})$, where $h, c, \lambda, N_0, \Delta, w, d, D, \tau_{\rm th}, I_{\rm bias}, I_{\rm c}$ are the Plank's constant, speed of light, cutoff wavelength, density of states at the Fermi level, superconducting energy gap, width and thickness of the nanostrip, electronic diffusivity, electronic thermalization time, bias current, and critical current of the nanostrip, respectively [16], [17]. Therefore, a material having small N_0, small Δ, small D, and short $\tau_{\rm th}$ is preferable for longer wavelength detection.

The count rate is determined by the response time $\tau = \tau_{\rm rise} + \tau_{\rm fall}$, where $\tau_{\rm rise}$ and $\tau_{\rm fall}$ are the rise time and decay time of the voltage pulse, respectively. From the electrical circuit model, $\tau_{\rm rise} = L_{\rm k}/(Z_0+R_n(t))$ and $\tau_{\rm fall} = L_{\rm k}/Z_0$, where $L_{\rm k}$, $R_n(t)$ and Z_0 are the kinetic inductance of the nanostrip, time dependent hotspot resistivity, and load impedance of the circuit, respectively [18]. Because $L_{\rm k} = (\mu_0\lambda_{\rm L}^2)(l/A)$, where μ_0, $\lambda_{\rm L}$, l, and A are the permeability of vacuum, the magnetic penetration depth, the length, and the cross-section of the nanostrip, respectively, a material having small $\lambda_{\rm L}$ is preferable for detecting high count rate. There is a limitation even if it is possible to increase the count rate of SNSPD by decreasing $L_{\rm k}$. If $\tau_{\rm fall}$ becomes shorter than a thermal relaxation time $\tau_{\rm cool}$, the current return back to the nanostrip before the nanostrip return to the superconducting state, and self-heating hotspot remains, known as latched state. A material having a small $\tau_{\rm e-ph}$ is preferable for detecting high count rate because $\tau_{\rm cool}$ is set by electron-phonon interaction time $\tau_{\rm e-ph}$ and phonon escape time to the substrate $\tau_{\rm esc}$. The internal detection efficiency (IDE) decreases as $\tau_{\rm e-ph}$ is small because the hotspot cools rapidly because of the rapid energy transfer from electron to phonon.

For SNSPD's high-temperature operation, a material with a high-superconducting transition temperature ($T_{\rm c}$) is required. However, the detection wavelength limit is shortened because Δ also becomes large for high $T_{\rm c}$ material.

In selecting the material, it is necessary to consider the material parameters and technical problems of fabrication. SNSPD usually needs ultrathin films with 5-nm thickness and nanostrips with 100-nm width, and the technology of thin film growth and nanofabrication process strongly depends on the material. Generally, IDE and the detection wavelength limit are improved as the cross-section of the nanostrip is reduced. However, when the cross-section becomes too small and $I_{\rm c}$ decreases below approximately 10 μA, the jitter increases as the voltage pulse's noise increases. Hence, a material with high critical current density ($j_{\rm c}$) is desirable to reduce the cross-section of the nanostrip.

This paper reviews the progress made so far in developing SNSPD using various superconductors and discusses prospects.

2. Nb-Based SNSPDs

2.1 NbN and NbTiN

NbN ($T_{\rm c}$ = 17 K) is the first superconductor used for

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[†]The author is with the Kitami Institute of Technology, Kitami-shi, 090–8507 Japan.
a) E-mail: shibathr@mail.kitami-it.ac.jp
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[*]SNSPD is traditionally known as superconducting nanowire single-photon detector; the IEC standard recommends the use of "nanostrip" instead of "nanowire" (IEC 61788-22-1).

SNSPD [1]. NbN-SNSPD is the most widely used because it can operate using a Gifford-McMahon (GM) cryocooler with high SDE, low jitter, low DCR and high CR [8], [10], [19]. For NbN-SNSPD, the commonly used film is the polycrystalline NbN ultrathin film, which is usually deposited on a thermally oxidized Si substrate or on a distributed Bragg mirror (DBR) films by a DC magnetron sputtering of a niobium target in a mixture of argon and nitrogen gases. There are many studies in obtaining an ultrathin film with smooth surface and high T_c and j_c, in which it is effective to use a large niobium target with a 6-in diameter and/or add a RF bias to the substrate holder during sputtering [19], [20]. Recently, atomic layer deposition (ALD) grew the ultrathin NbN film with exceptional homogeneity [21], [22]. The SNSPD using ALD film shows saturated IDE over a broad bias range.

Instead of the polycrystalline film, the epitaxial NbN thin film is grown by the sputtering on a MgO(100) substrate [19]. Although the epitaxial film shows higher T_c and j_c and lower resistivity than the polycrystalline film, the SDE of the device using epitaxial film is not high because the I_c of the device is limited by local constrictions in the nanostrip, caused by defects in the epitaxial film [23]. Molecular beam epitaxy (MBE) on AlN-on-sapphire substrate also grew the epitaxial NbN film [24]. The SNSPD using MBE film shows saturated IDE at 1050 nm, which may due to fewer defects in the epitaxial film.

For the nanofabrication of NbN-SNSPD, electron beam lithography and reactive ion etching (RIE) using CF_4 or SF_6 gas are commonly used. Instead of the e-beam lithography, nanofabrication using local oxidation with an atomic force microscope (AFM), nano-imprint lithography, and nonlinear femtosecond optical lithography are also reported [25]–[27].

Korneeva *et al.* recently reported a single-photon detection in micron-wide NbN bridge, which has an I_c close to a theoretical depairing current [28]. The bridge shows saturated IDE in the high bias region. The NbN-SNSPD using micron-wide bridge may become a single-photon detector with a high count rate and large detection area.

NbTiN (T_c = 16 K) is also frequently used for SNSPD. NbTiN-SNSPD is expected to operate faster than NbN-SNSPD because the L_K of NbTiN is approximately 25% lower than that of NbN [29]. The performance of NbTiN-SNSPD grown by co-sputtering of niobium and titanium is high and comparable with that of NbN-SNSPD [9], [30].

2.2 Nb, NbC, NbSi, and NbRe

Single-photon detection at visible wavelength is reported in Nb (T_c = 9.25 K) based SNSPD fabricated by the sputtering and the e-beam lithography [16], [31]. However, the Nb-SNSPD is easily latched because of the long τ_{e-ph}.

Single-photon detection at 405 nm is also reported NbC (T_c = 12 K) based SNSPD fabricated by a pulsed laser deposition (PLD) in hydrocarbon atmosphere and the e-beam lithography [32]. The detection efficiency of NbC-SNSPD is low and doesn't have a single-photon sensitivity at longer wavelength because D of NbC is 4.45 cm^2/s, which is approximately 10 times larger than that of NbN.

Dorenbos *et al.* fabricates NbSi-SNSPD (T_c = 2 K) by co-sputtering and e-beam lithography [33]. Single-photon sensitivity was confirmed to down by 1900 nm because of the small Δ.

NbRe (T_c = 9 K) thin film fabricated by sputtering is robust for deposition and lithographic process. NbRe-SNSPD shows a saturated IDE at 1301-nm wavelength at 2.8 K. It is possible to fabricate SNSPD with a low-filling factor of meander because the refractive index and extinction of NbRe are higher than that of other materials used for SNSPD [34].

3. Amorphous-Based SNSPDs

3.1 WSi

WSi (T_c = 4.9 K) based SNSPD shows a saturated SDE over 90% in a wide-bias range at the telecommunication wavelength [7]. It is possible to fabricate a uniform homogeneous WSi nanostrip without degrading its superconducting properties because WSi film is amorphous. The large hotspot size owing to a small Δ and long τ_{e-ph} results in high SDE. The shortage of WSi-SNSPD is the low-operation temperature and the large jitter due to the small I_{bias}. WSi-SNSPD is fabricated by the co-sputtering of tungsten and silicon, the sputtering of Si cap layer to prevent oxidation, the e-beam lithography, and the RIE using the fluorine-based gas.

3.2 MoSi and MoGe

It is also possible to fabricate the uniform and homogeneous nanostrip without degradation because MoSi (T_c = 7.5 K) film is also grown as amorphous by co-sputtering [6], [35]–[37]. The SDE of MoSi-SNSPD reaches a record of 98% at 1550 nm in a wide-bias range [6]. The fabrication process is almost the same as that of WSi-SNSPD. MoSi-SNSPD works at a higher temperature than WSi-SNSPD because of the higher T_c of MoSi than WSi.

MoGe (T_c = 6.8 K) based SNSPD also shows a saturated IDE at the telecom wavelength by its amorphous structure [38]. MoGe-SNSPD also shows a lower jitter and higher-operating temperature than that of WSi-SNSPD with its larger I_c and higher T_c.

4. Nitride-Based SNSPDs

4.1 MoN

MoN-SNSPD shows a saturated IDE in a wide bias range at 1064 nm [39]. The reason of high IDE is a large hot-spot size owing to a long τ_{e-ph} of MoN. MoN has several phases, such as γ-Mo_2N (T_c = 7 K), β-Mo_2N (T_c = 5 K), δ-MoN (T_c = 12 K). Polycrystals of γ-Mo_2N become dominant when the film is grown by the reactive sputtering of molybdenum target in the mixture of argon and nitrogen gases. For the nanofabrication of MoN, e-beam lithography and the RIE of fluorine-based gas are used.

4.2 TaN and VN

TaN (T_c = 10.5 K) based SNSPD shows IDE higher than NbN-SNSPD because of the small Δ and small N_0 [40]. TaN-SNSPD is fabricated by magnetron sputtering, e-beam lithography and the Ar-ion milling.

VN (T_c = 9 K) based SNSPD also shows a saturated IDE at 900-nm wavelength [41]. VN-SNSPD is fabricated by the reactive sputtering of vanadium, e-beam lithography and dry etching using SF_6.

5. MgB_2-SNSPD

Since magnesium diboride (MgB_2) has T_c of 39 K and a short τ_{e-ph} of 2 ps, it is expected to become an SNSPD that can operate at a higher temperature and higher count rate than NbN-SNSPD [42]. MgB_2-SNSPD detects at 11 K for a photon in a visible range and at 13 K for a single biomolecular ion [43]–[46]. Recently, MgB_2-SNSPD works more than 10 times faster than NbN-SNSPD [47]. Although these results promise well for the future of MgB_2-SNSPD, the major problem is the low IDE in the near-infrared region. The SDE of MgB_2-SNSPD is below 1% because of the large superconducting gap Δ and the very short τ_{cool}. Alternatively, 100% detection efficiency is reported for the detecting high-energy particles, such as single biomolecular ions [46].

The 10 nm-thick MgB_2 films with T_c = 20 K are grown by the MBE [43], [48]. Recently, using a hybrid physical chemical vapor deposition (HPCVD), the 5 nm-thick films with T_c > 30 K are reported [47], [49], [50].

For the nano-fabrication of MgB_2, Ar ion milling is usually used [42], [47]. It is necessary to deposit a protective film such as Au, SiO_2, or AlN on MgB_2 film to prevent damage during Ar ion milling. The dry etching using Br_2-N_2 gas is also reported for the nanofabrication of MgB_2 [45].

6. Iron-Based SNSPDs

Iron-based superconductors are newly discovered materials with high T_c, making them a candidate for SNSPDs that can operate at high temperatures. Furthermore, because iron-based superconductors are resistant to a strong magnetic field, iron-based SNSPD may be used for photon/particle detector under a strong magnetic field, which is desirable in the field of nuclear and high-energy physics [5]. Although single-photon sensitivity has not yet been reported, there are several reports on iron-based nanostrip fabrication [51]–[53]. Yuan *et al.* fabricated a 10 nm-thick Co doped $BaFe_2As_2$ thin film by PLD and processed it into a nanostrip with 200-nm width by Ar ion-beam etching and Cr mask [51]. The nanostrip has a T_c^{zero} of 20 K and a high J_c of 1.8×10^7 A/cm^2 even at 10 K. Tsuji *et al.* fabricated a (00l) oriented 23.5 nm-thick NdFeAs(O,F) thin film by MBE and processed it into a nanostrip with 840-nm width by Ar ion-beam etching [52]. The nanostrip has a T_c^{zero} above 40 K and a J_c above 5×10^6 A/cm^2.

Presently, hysteretic current-voltage characteristics necessary for SNSPDs, are not observed in the iron-based nanostrips. Further reduction of the nanostrip's size with hysteretic I-V characteristics is required to realize iron-based SNSPDs.

7. Cuprate-Based SNSPDs

There have been several reports towards a cuprate-based SNSPD because it may work at high temperatures because of its high T_c [54]. The pump-probe measurement of cuprate films also reveals that films exhibit picosecond photoresponse because of their strong electron correlation [55], which is important to realize faster SNSPDs. Thus, the cuprate-based SNSPD as the ultrafast single-photon detector working at high temperature is expected. However, it is technologically challenging to fabricate a high quality cuprate nanostrip with a 5 nm-thick and 100 nm-wide dimension. Most of the early reports of cuprate nanostrip did not have the hysteretic I-V characteristics, which indicated that the nanostrips are damaged and cannot be used for single-photon detection. Recently, there are several reports with hysteretic I-V characteristics by improving the ultra-thin film growth and nanofabrication process. However, the single-photon sensitivity using cuprate nanostrip is not yet achieved.

7.1 $YBa_2Cu_3O_{7-\delta}$

$YBa_2Cu_3O_{7-\delta}$ is the most extensively studied for cuprate-based SNSPD because of its high T_c of 92 K [54], [56]–[61]. Lyatti *et al.* grew a 5.8 nm (5 unit cell) thick $YBa_2Cu_3O_{7-\delta}$ thin film with T_c = 85 K on an $SrTiO_3$ substrates by dc sputtering and processed it into a nanostrip with 5-μm width by wet etching [57]. Although the J_c of the first three unit cell layers adjacent to the substrate were low, the J_c of the two upper layer reached 1.01×10^7 A/cm^2. Ejrnaes *et al.* fabricated $YBa_2Cu_3O_{7-\delta}$ nanostrip with 10 nm-thickness and 65 nm-wide by PLD and Ar ion-beam etching with carbon mask. The nanostrip has hysteretic I-V characteristics, and J_c reaches 2.2×10^7 A/cm^2. The voltage pulse due to dark count was also observed in the high-bias region (I_{bias} > 0.98 I_c) at 4.9 K [59]. Recently, Xing *et al.* fabricated a nanostrip with 10-μm width and 100-nm thickness by PLD and selective epitaxial growth method. The J_c of the nanostrip was 5.5×10^5 A/cm^2 at 77 K and showed a photoresponse above 85 K [61].

7.2 $La_{1.85}Sr_{0.15}CuO_4$

A 5 nm-thick $La_{1.85}Sr_{0.15}CuO_4$ film with T_c = 42 K is epitaxially grown on $LaSrAlO_4$ substrate by MBE [62], [63]. The nanostrip with 100-nm width and 5-nm thickness fabricated by the Ar ion milling showed hysteretic I-V characteristics

Table 1 Summary of various superconductors used for SNSPD.

Material	T_c (K) (bulk)	T_c (K) (device)	Single-photon sensitivity	Deposition method	Nanostrip width (nm) × thickness (nm)	Etching (milling) gas	Comments	References
NbN	17	8.6	Y	Sputtering, ALD, MBE	75 × 8	CF_4, SF_6	SDE > 90 % (1550 nm)	8, 10, 21, 22, 24
NbTiN	16	~10	Y	Sputtering	50 × 8.4	CF_4, SF_6	SDE > 90 % (1550 nm)	9
Nb	9.25	4.5	Y (690nm)	Sputtering,	100 × 7.5	CF_4, SF_6		16, 31
NbC	~12	11.2	Y (405nm)	PLD	145 × 23	SF_6		32
NbSi	-	2	Y	Sputtering	160 × 10	SF_6 + He		33
NbRe	9	6.03	Y	Sputtering	50 × 8	SF_6 + O_2	Saturate IDE (1301 nm)	34
WSi	4.9	3.7	Y	Sputtering	120 × 5	SF_6	SDE = 93 % (1550 nm)	7
MoSi	7.5	~4.8	Y	Sputtering	80 × 4.1	SF_6	SDE = 98 % (1550 nm)	6
MoGe	6.8	4.4	Y	Sputtering	110 × 7.5	SF_6	Saturate IDE (1550 nm)	38
MoN	12	5.4	Y	Sputtering	83 × 3.6	SF_6	Saturate IDE (1064 nm)	39
TaN	10.5	8.16	Y	Sputtering	126 × 3.9	Ar	Saturate IDE (300 nm)	40
VN	9	5.5	Y	Sputtering	115 × 6	SF_6	Saturate IDE (900nm)	41
MgB_2	39	32	Y	HPCVD, MBE	35 × 5	Ar , B_{r2} + N_2	Single-photon sensitivity at 11 K	45, 48
$Co\text{-}BaFe_2As_2$	~25	20	N	PLD	200 × 10	Ar	No hysteretic I-V	52, 54
NdFeAs(O,F)	~51	40	N	MBE	840 × 23.5	Ar	No hysteretic I-V	53
$YBa_2Cu_3O_7$	92	85	N	PLD, sputtering	65 × 10	Ar	DCR observed Photoresponse at 85 K	60, 62
$La_{1.85}Sr_{0.15}CuO_4$	37	42	N	MBE	100 × 5	Ar	Photoresponse at 30 K	64
$Pr_{1.85}Ce_{0.15}CuO_4$	24	16	N	PLD	100 × 75	Ar	Hysteretic I-V	65

and a high J_c of 2.3×10^7 A/cm^2 and shows a photoresponse up to 30 K with a bias current just below I_c [63].

7.3 $Pr_{1.85}Ce_{0.15}CuO_4$

Electron-doped cuprate is also tried realizing SNSPD [64]. Charpentier *et al.* grew 75-nm-thick $Pr_{1.85}Ce_{0.15}CuO_4$ films with T_c = 16 K and processed it into a nanostrip with 100-nm width by Ar ion etching using carbon mask. The nanostrip showed hysteretic I-V characteristic and $J_c = 4.1\times10^6$ A/cm^2.

8. Conclusions

SNSPDs using various superconductors are reviewed, which are summarized in Table 1. The Nb(Ti)N-SNSPDs and amorphous-based SNSPDs are currently exceptionally highest performance single-photon detectors, and contribute to significant progress in many advanced scientific fields. To further expanding the use of SNSPDs, increasing the operating temperature seems to be one of the most important factor. Thus, it is desirable to use high-T_c materials for SNSPD without degrading its performance.

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Hiroyuki Shibata received his B.S., M.S., and Ph.D. degrees in Physics from the Waseda University, Tokyo, Japan, in 1985, 1987, and 1997, respectively, He has been working on the physics, material development, device fabrication, and application to quantum information of superconductors. Since 2015, he has been a professor at Kitami Institute of Technology, Japan. He is a member of the Physical Society of Japan, the Japan Society of Applied Physics, and the Institute of Electronics, Information, and Communication Engineers.