Cavity-Enhanced Superconducting Single-Photon Detectors on GaAs Substrate

S. Jahanmiri Nejad,[1,*] A. Gaggero,[2] D. Bitauld,[1,†] F. Marsili,[1,3,‡] D. Sahin,[1] F. Mattioli,[2] R. Leoni,[2] G.H. Hamhuis,[1] R. Nötzel,[1] R. Sanjines,[3] and A. Fiore[1]

[1] COBRA Research Institute, Eindhoven University of Technology, Eindhoven, The Netherlands
[2]Istituto di Fotonica e Nanotecnologie, CNR, Roma, Italy
[3]Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland
[*]*s.jahanmiri.nejad@tue.nl*

Nanowire superconducting single photon detectors (SSPDs) are unique detectors for many applications in quantum information and communications technology, owing to their ultrafast photoresponse, low dark count rate and low timing jitter. However, they have limited detection efficiency due to small optical absorption in ultrathin wires. A promising approach to increase the photon absorption in SSPDs, is integrating them with advanced optical structures. We demonstrate the successful integration of SSPDs with optical microcavities based on GaAs/AlAs Bragg mirrors. Characterization of these devices reveals clear cavity enhancement of the detection efficiency, resulting in a peak value of 18% at λ=1300nm and T=4.2K.

Introduction

Single photon detectors (SPDs) are essential components for a variety of potential applications ranging from biomedical imaging and VLSI circuit testing to quantum information and ultralong-distance optical communication [1]. Particularly in the last decade, the emergence of a novel SPD technology based on superconducting nanowires has drawn a considerable attention in this field [2]. Nanowire superconducting SPDs (SSPDs) are ultrathin, submicron wide NbN wires which are arranged in a meander-like geometry. SSPDs are cooled down well below the critical temperature (~10K for ultrathin NbN layers) to operate in superconducting state. The photon detection process is based on formation of a resistive section in the nanowire upon absorption of an incoming photon [2].
SSPDs offer broad spectral response from ultraviolet to infrared wavelengths, high count rate, low dark count rate and small timing jitter. Another important parameter is detection efficiency (DE), which is defined as the ratio of the number of counted photons to the number of photons incident on the device active area. Low absorption in the ultrathin nanowire structures limits detection efficiency below 30%. One approach to enhance absorptance is integration of the SSPDs with optical cavities [3,4,5].
In this paper we report on our recent progress toward integration of SSPDs with optical cavities based on GaAs/AlAs distributed Bragg reflector (DBR). The GaAs/AlAs Bragg technology provides very high reflectivities >99% and allows the integration of SSPDs with a bottom mirror, and is therefore compatible with the top-illumination, as opposed to the top mirror approach reported in [3]. We describe the design procedure and

[†]D. Bitauld is currently with Photonics Theory Group, Tyndall National Institute, Cork, Ireland.
[‡]F. Marsili is currently with the Department of Electrical Engineering and Computer Science, MIT, Cambridge, USA.

present experimental results of the spectral dependence of the optical absorption and detection efficiency of a fabricated device.

Design and Fabrication

The detector structure is shown in figure 1(a,b). The optical cavity is formed by a Bragg reflector on a GaAs substrate (bottom mirror) and a weak top mirror (epitaxial GaAs/air interface). The DBR is designed to be resonant at 1309nm under normal illumination at 4K. It consists of 14.5 periods of 113nm AlAs /96.7nm GaAs. It is capped by a 193.9 nm GaAs layer, acting as a λ/2 spacer between bottom and top mirrors. Calculations using a 1D transfer matrix model [6] show a peak absorptance of 83.2% at resonance for a meander made of a 4nm-thick film, with filling factor=40% and polarization parallel to the wires (see figure 1(c)). The meander is considered as a uniform medium with effective dielectric constant between air and NbN, where refractive index of NbN is assumed to be n_{NbN}=5.23+5.82i [7]. Figure 1(d) depicts the spatial dependence of the normalized modulus square of the electric field, (left axis, red) and the real part of the refractive index, (right axis, blue) of the designed detector on DBR structure. The electric field is maximum at the position of the NbN layer.

The DBR was grown by molecular beam epitaxy on an undoped, (100)-oriented GaAs substrate. An NbN film with thickness in the range of 3-5nm is deposited on the epitaxial GaAs top layer by dc reactive magnetron sputtering technique with an Nb target (99.99% pure) in nitrogen ambient. The optimized NbN ultrathin film deposition on GaAs requires lower temperature as compared to the case of sapphire, MgO or Si substrates due to arsenide evaporation. In our case, the growth temperature is fixed at 350°C. Detailed description of the film growth can be found in [8].

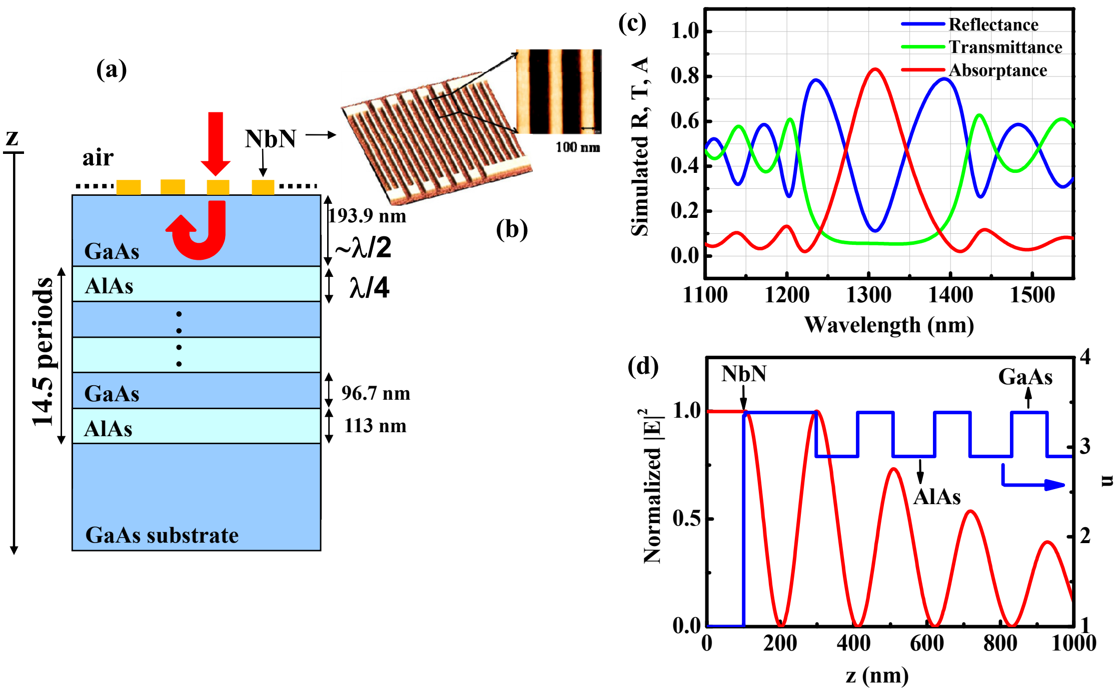

Figure 1. Design of the SSPD based on the DBR. (a) Layers structure (b) AFM image of an NbN meander fabricated on the GaAs substrate (c) Simulated reflectance R, transmittance T, and absorptance A, of the SSPD. The peak absorptance reaches ~83% at 1309nm. (d) Spatial dependence of the normalized modulus square of the electric field, $|E|^2$ (left axis, red) and real part of the refractive index, n (right axis, blue)

Experimental Results

In order to assess the performance of the SSPDs on the DBR structures, low-temperature electrical and optical characterizations of the devices were performed. The current-voltage characteristics measured at T=4.2K with a dipstick in liquid helium show a critical current I_c=16.4μA. Figure 2(a) shows the measured reflection spectra of the DBR structure with and without the patterned NbN nanowire on top (measured at T=5K using a lens with numerical aperture NA=0.5). The DBR reflection band extends from 1200nm to 1370nm, with a small dip around 1300nm when no NbN film is present (dark blue line, left axis). Upon deposition and patterning of the NbN thin film, the dip becomes much more noticeable (dark green line, left axis) which is the evidence of the optical absorption in the NbN wires. While the absolute wavelength of the resonance may be affected by the refractive index and the angle of incidence, the skewed shape of the measured reflection spectra reveals an asymmetric deviation in the thicknesses and/or indices of the GaAs and AlAs layers as compared to the design values. As is shown in figure 2(a), a nice fit is achieved to the measured reflectance of the DBR by considering 5% thicker GaAs layers and 8% thinner AlAs layer (light blue open circles, left axis).

Furthermore, to be able to fit the measured reflection spectrum of the SSPD, the effective refractive index of NbN is required to be lower than the value used for the design of DBR structure [6]. This is conceivable since the refractive index depends on the device thickness and temperature and the wavelength of the incident light. In figure 2(a), in order to get the good fit to the SSPD reflectance, (light green open squares, left axis) n_{NbN}=3.4+4i at 1300nm was assumed. As a result, based on the measured reflectance of DBR and SSPD, the absorption spectrum of the NbN is simulated (figure 2(a) red line, left axis). In this case, around 50% absorptance can be achieved. The cavity design may be improved by adding a top dielectric DBR to further increase the absorption in the film.

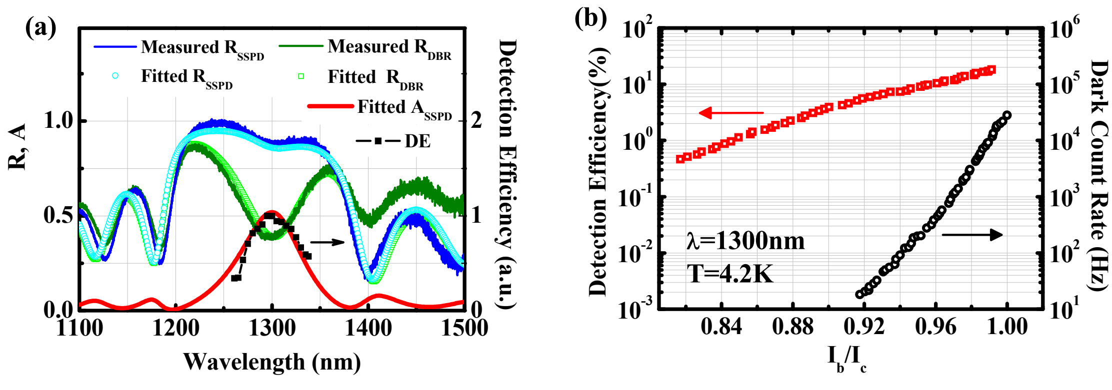

Figure 2. (a) Left axis: measured and fitted reflectance of the DBR structure and the SSPD, together with the corresponding simulated absorption spectrum of the SSPD. Right axis: Experimental detection efficiency vs. wavelength for an SSPD on DBR, using a tunable laser at I_b=13μA (b) Detection efficiency measured at 1300nm (red squares, left axis) and dark count rate (black circles, right axis) at 4.2K as a function of the normalized bias current for the same device as (a).

The detection efficiency of the device is shown (in arbitrary units) vs. wavelength in Fig. 2(a) (black symbols, right axis), as measured using a tuneable laser in a cryogenic probe station, with a device temperature T=5-6 K and a bias current I_b=13μA. A clear resonance is observed in the DE, centered at ~1300 nm, which corresponds very well to the absorption spectrum of the device. The polarization was controlled to maximize the number of detector counts, corresponding to an electric field parallel to the nanowires. Figure 2(b) shows the DE and dark count rate (DCR) for the same device in a dip-stick at 4.2 K under illumination at 1300nm. The usual increase of both DE and DCR vs. bias current is observed, with a maximum DE=18.3 % at I_b=0.99 I_c. The fact that the peak DE is lower than the expected absorptance of 50% is attributed to the limited intrinsic efficiency of the device [9]. Lower measurement temperatures and further fine tuning of the film thickness and deposition conditions will enable reaching the absorption-limited DE value.

Conclusion

We have demonstrated the first superconducting single-photon detectors compatible with monolithic integration based on the well-developed III-V technology. Design, fabrication and characterization of SSPDs on AlAs/GaAs DBR structures are carried out. The DBR structure is designed for peak absorptance of 83.2% at resonance for a 4nm thick NbN meander. Fabricated SSPDs on DBR show an improved performance with a peak detection efficiency of 18.3% at λ=1300nm and T=4.2K.

Acknowledgments

This work was supported in part by the European Commission through FP6 STREP "SINPHONIA" (contract number NMP4-CT-2005-16433) and by FP7 QUANTIP (contract number 244026).

References

[1] R. H. Hadfield, "Single photon detectors for optical quantum information applications," Nature Photonics, vol. 3, 696, 2009.

[2] G.N. Gol'tsman, O. Okunev, G. Chulkova, A. Lipatov, A. Semenov, K. Smirnov, B. Voronov, A. Dzardanov, C. Williams, and R. Sobolewski, " Picosecond superconducting single-photon optical detector," Appl. Phys. Lett. vol. 79, 705, 2001.

[3] K.M. Rosfjord, J.K.W. Yang, E.A. Dauler, A.J. Kerman, V. Anant, B.M. Voronov, G.N. Gol'tsman, and K.K. Berggren, "Nanowire single-photon detector with an integrated optical cavity and anti-reflection coating," Opt. Express, vol. 14, No. 2, 527–534, 2006.

[4] B. Baek, J.A. Stern, and S.W. Nam, "Superconducting nanowire single-photon detector in an optical cavity for front-side illumination," Appl. Phys. Lett. vol. 95, 191110, 2009.

[5] M.G. Tanner, C.M. Natarajan, V.K. Pottapenjara, J.A. O'Connor, R.J. Warburton, R.H. Hadfield, B. Baek, S. Nam, S.N. Dorenbos, E. Bermúdez Ureña, T. Zijlstra, T.M. Klapwijk, and V. Zwiller, "Enhanced telecom wavelength single-photon detection with NbTiN superconducting nanowires on oxidized silicon," Appl. Phys. Lett. vol. 96, 221109, 2010.

[6] A. Yariv and P. Yeh, "Optical Waves in Crystals", Wiley ed., chap. 6, 2003.

[7] V. Anant, A.J. Kerman, E.A. Dauler, J.K.W. Yang, K.M. Rosfjord, and K.K. Berggren, "Optical properties of superconducting nanowire single-photon detectors," Optics Express, vol. 16, 10750, 2008.

[8] A. Gaggero, S. Jahanmiri Nejad, F. Marsili, F. Mattioli, R. Leoni, D. Bitauld, D Sahin, G.J. Hamhuis, R. Nötzel, R. Sanjines, and A. Fiore, "Nanowire superconducting single-photon detectors on GaAs for integrated quantum photonic applications," Appl. Phys. Lett. vol. 97, 151108, 2010.

[9] A. Semenov, P. Haas, H.W. Hübers, K. Ilin, M. Siegel, A. Kirste, D. Drung, T. Schurig, A. Engel, "Intrinsic quantum efficiency and electro-thermal model of a superconducting nanowire single-photon detector," J. of Modern Optics, vol. 56, Nos. 2-3, 2009.