This manuscript has been previously reviewed at another journal. This document only contains reviewer comments and rebuttal letters for versions considered at Communications Physics

Reviewers' comments:

Reviewer #1 (Remarks to the Author):

The authors have significantly improved the manuscript and have properly addressed all issues raised in my previous report. I recommend accepting the paper after minor revision. Here are the few remaining points, which need to be corrected:

1. I think the sentence in the abstract

"After long competition of suspended cooling platform and direct electron cooling, the CEB demonstrates ultimate performance in contrast to problems with a cooling platform"

is a bit out of place. In my opinion, the abstract should briefly report main results of the experiment, which are rather impressive, while the discussion about the advantages or disadvantages of various cooling mechanisms should be postponed to the discussion section.

2. At the end of line 197 the phrase is cut abruptly. Here the text should be edited.

3. The equation in line 565 contains the exponent $e^{-\Delta(T_S)/\tau_S}$. Here τ_S should be replaced by the temperature of the superconductor T_S.

4. Finally, I recommend the authors to proof read the text once again. Typos and grammatically incorrect phrases are still remaining in the text.

Reviewer #2 (Remarks to the Author):

The authors report on SINIS cold electron bolometer (CEB) system where intrinsic electron refrigeration of the biased NIS junctions works favorably to improve the NEP (cool the electrons) while at the same time providing the transduction method for the bolometric response. I find the work interesting, but the manuscript has some shortcomings that have to be fixed before publication can be considered.

1. Language problems: please proof read carefully. There are several issues with the language. Also there are sentences where the end is missing (line 197).
2. Abstract: I would advise to drop/change “unreachable for TES (Transition Edge Sensor) using heating instead of cooling, and KID (Kinetic12 Inductance Detector) at the same temperature.” Better to keep such statements in the bulk of the paper. Is there actual solid proof of this statement?
3. Lines: 18-21: ”The tendency in bolometer development is such, that the increase in sensitivity,…, is reached by lowering the operation temperature of the bolometer.” I know that there are also high temperature (and room temperature) bolometers. How do they fit with this statement? For example, think about recently introduced nano-thermoelectric thermal detectors https://aip.scitation.org/doi/10.1063/1.4989683 .
4. Eq. 1: This equation is an approximation (based on ref [8] (Golubev et al. JAP)). Maybe add a few words of validity of the equation?
5. Eq. 1: Related to above, please note that the Equation assumes metal abosorber. There are different power laws and coupling constants in different materials. An example is doped silicon variant utilized in https://aip.scitation.org/doi/10.1063/1.4892069 . Please mention this difference and cite the paper.
6. SIN vs. NIS. I think NIS is more established.
7. Lines 42-45: The cooling principle is appropriately introduced. However, the text does not mention, why only the high-energy electrons can tunnel out of the normal metal.
8. Lines 81-110: This section might be hard to follow for non-expert reader, since the antenna is

only introduced in lines 106-107. Introduce the whole design at a single go.
9. Lines 125-144: The sample material and parameters are listed in Methods. However, I was expecting them to show up at the same place, where sample layout and schematics are discussed. Please add here at least a notion, that the sample parameters and materials are discussed in the Methods. Also, why not mention, that the normal metal absorber is FeAl, if that is one of the cool things in this paper? Also, maybe a mention that the superconductor is aluminium with optimum cooling point of 300 mK, might be relevant.
10. Line 147: Where does the limit 0.5 pW come from? Do you have a reference?
11. Fig. 2-A: the colors of the labels and the figure do not match (i.e. orange label, red dataline).
12. Lines 190-197: Where does the black-body radiation originate from? How is it located in relation to the bolometer array? How big portion of the radiation reaches the bolometer array?
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15. Line 226-230: figure 3-A. When determining the sample parameters, how was the asymptotical resistance (R in reference [8]) defined? Where the measurements extended to the asymptotic range?
16. Equations (3): Have terms T_E, T_PH, \delta I etc. been introduced anywhere?
17. Lines 246-247: I think here is a typo responsivity should be S_V not V_ND/S_V or did you mean V_ND/dP_Source? Also how is the responsivity defined? Is it a measured quantity or deduced from equation (1) of the article?
18. Lines 254-256: Here it is claimed that the amplifier noise dominates over NEP_eph and NEP_SIN. However, in figure 3-A the amplifier noise is smaller than these components. Please explain.
19. Lines 283-293: Is it true that if the IV-curves coincide, the amplifier and NIS-NEPs are about equal? Here the data are measured in two different temperatures and the temperature affects at least the responsivity of the device.
20. Line 297-299: Figure 3-C does not demonstrate that photon NEP is larger than amplifier NEP even though that is claimed in the text. The amplifier NEP is not included in said figure.
21. Line 346: What is dark NEP?
22. Lines 350-360: The authors study a single bolometer. Is the point to demonstrate the ultimate limit of a device? Can a single bolometer ever be used to measure anything practical?
23. Figure 4: The NEP_amp in the legend of both figures indicates that this component comes from the same source. Change the legend 4-B to NEP_amp,cold etc.
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28. Lines 510-511: How much lighter and cheaper is a He3-pot compared to dilution refrigerator? That is of course the first step towards the higher operation temperatures, but is increase from 20 mK to 300 mK world changing achievement?
29. Line 516-518: How is developing an on-chip refrigerator relevant to this paper? Especially as the authors have claimed above that CP is much worse way to do thing compared to CEB.
30. Methods, lines: 544-555: what is P_S? It is explained in reference [16] but should also be elaborated here! Where does the Joule heating come from? Heating due to resistivity of the absorber?
31. Supplementary Note 1: Where does G_cool come from? Is it P_cool/\Delta T?
32. Supplementary Note 1: Where do the timeconstants come from? Please add a reference.
33. Supplementary Note 1: What is gamma?
34. Supplementary Note 2: Please tell the spacing of the powers. Now only the maximum and

minimum values given.

35. Eq. 5: S electrodes are finite connecting to normal metal antenna. What is the consequence of neglecting spatial dependency in Eq. 5?

36. Please note that it is quite tedious to read the left column of the text as the line numbers of the right column are attached to it. For the referees' sake please fix this in the next round.

First of all, we would like to thank reviewers for valuable remarks made this manuscript more understandable for a broad audience.

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Comment:
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"After long competition of suspended cooling platform and direct electron cooling, the CEB demonstrates ultimate performance in contrast to problems with a cooling platform"
is a bit out of place. In my opinion, the abstract should briefly report main results of the experiment, which are rather impressive, while the discussion about the advantages or disadvantages of various cooling mechanisms should be postponed to the discussion section.

Reply:
This sentence is removed from the abstract.

Comment:
2. At the end of line 197 the phrase is cut abruptly. Here the text should be edited.

Reply:
It happened due to one column figure, which had changed the formatting. The continuation of this sentence was at line 198, which was placed at the right. Now we have fixed this issue and line 198 is now placed below line 197.

Comment:
3. The equation in line 565 contains the exponent e^{-\Delta(T_S)/\tau_S}. Here τ_S should be replaced by the temperature of the superconductor T_S.

Reply: Corrected.

Comment:
4. Finally, I recommend the authors to proof read the text once again. Typos and grammatically incorrect phrases are still remaining in the text.

Reply: Corrected. We used the AIP English correction service.

Reviewer #2 (Remarks to the Author):

The authors report on SINIS cold electron bolometer (CEB) system where intrinsic electron refrigeration of the biased NIS junctions works favorably to improve the NEP (cool the electrons) while at the same time providing the transduction method for the bolometric response. I find the work interesting, but the manuscript has some shortcomings that have to be fixed before publication can be considered.

Comment:

1. Language problems: please proof read carefully. There are several issues with the language. Also there are sentences where the end is missing (line 197).

Reply: Corrected. We used the AIP English correction service.
About line 197: It happened due to one column figure, which had changed the formatting. The continuation of this sentence was at line 198, which was placed at the right. Now we have fixed this issue and line 198 is now placed below line 197.

Comment:

2. Abstract: I would advise to drop/change "unreachable for TES (Transition Edge Sensor) using heating instead of cooling, and KID (Kinetic12 Inductance Detector) at the same temperature." Better to keep such statements in the bulk of the paper. Is there actual solid proof of this statement?

Reply:
The abstract is rewritten. The proof is that we did not find any published work with similar sensitivity for KID or TES at this temperature: such digits of NEP are written for much lower temperatures only.

Comment:

3. Lines: 18-21: "The tendency in bolometer development is such, that the increase in sensitivity,..., is reached by lowering the operation temperature of the bolometer." I know that there are also high temperature (and room temperature) bolometers. How do they fit with this statement? For example, think about recently introduced nano-thermoelectric thermal detectors https://aip.scitation.org/doi/10.1063/1.4989683.

Reply:
To our knowledge, the best sensitivity of the room temperature bolometers, achieved by today, is 10^{-13} $W/Hz^{1/2}$, and for a wide-spread Golay cell, the NEP is of order 10^{-11} $W/Hz^{1/2}$. While the cryogenic bolometers achieve sensitivities several orders of magnitude better: 10^{-18} - 10^{-17} $W/Hz^{1/2}$.
For example, in the cited article https://aip.scitation.org/doi/10.1063/1.4989683 the authors have measured sensitivity $13*10^{-12}$ $W/Hz^{1/2}$, which is of the same order of Golay cell sensitivity, and they plan to improve it by a factor of 10, which is still far away from sensitivities of the cryogenic bolometers.

Comment:

4. Eq. 1: This equation is an approximation (based on ref [8] (Golubev et al. JAP)). Maybe add a few words of validity of the equation?

Reply: Added: at temperatures $kT_e << \Delta$ and voltages $kT_e < eV < \Delta - kT_e$

Comment:

5. Eq. 1: Related to above, please note that the Equation assumes metal absorber. There are different power laws and coupling constants in different materials. An example is doped silicon variant utilized in https://aip.scitation.org/doi/10.1063/1.4892069 . Please mention this difference and cite the paper.

Reply:

Added: Let us note that the coupling constant Σ and the power law (\ref{Pe-ph}) varies for different materials. For example, in \cite{Brien14}, the CEB was realized with an absorber from doped silicon, which has a power 6 in P_{e-ph} dependence on temperature.

Comment:
6. SIN vs. NIS. I think NIS is more established.

Reply: Done. Now only NIS is used.

Comment:
7. Lines 42-45: The cooling principle is appropriately introduced. However, the text does not mention, why only the high-energy electrons can tunnel out of the normal metal.

Reply:
Added: With the increase of voltage, the high energy electrons get the possibility to tunnel first because there are available sates in the superconductor for them only above the gap.

Comment:
8. Lines 81-110: This section might be hard to follow for non-expert reader, since the antenna is only introduced in lines 106-107. Introduce the whole design at a single go.

Reply:
The paragraph is modified. Added: Coupling of external radiation is realized through the antenna, connected to superconducting leads.

Comment:
9. Lines 125-144: The sample material and parameters are listed in Methods. However, I was expecting them to show up at the same place, where sample layout and schematics are discussed. Please add here at least a notion, that the sample parameters and materials are discussed in the Methods. Also, why not mention, that the normal metal absorber is FeAl, if that is one of the cool things in this paper? Also, maybe a mention that the superconductor is aluminum with optimum cooling point of 300 mK, might be relevant.

Reply: We add the reference to Methods and also the sentence "The normal absorber is made of aluminum with thin (0.7 nm) underlayer of Fe, which destroys the superconductivity in aluminum."

Comment:
10. Line 147: Where does the limit 0.5 pW come from? Do you have a reference?

Reply: Yes, it is the reference [26], where the NEP had been calculated versus the bolometer number. It had been shown that for power load 5 pW the photon noise limited mode is reached starting from 6 bolometers in the array, which means that each bolometer obtains 0.5 pW.

Comment:
11. Fig. 2-A: the colors of the labels and the figure do not match (i.e. orange label, red dataline).

Reply: The lines are corrected and made thicker.

Comment:
12. Lines 190-197: Where does the black-body radiation originate from? How is it located in relation to the bolometer array? How big portion of the radiation reaches the bolometer array?

Reply: We add a scheme of the experimental setup to Supplementary materials. The black body is a copper cone, attached to the 4 K cryostat plate. The sample holder is attached to the 10 mK plate. Due to thermal decoupling of the black body and the sample we can change the black body temperature in a broad range, e.g., above 45K while keeping the coldest plate temperature at 0.3K.

Comment:
13. Lines 212-225: These lines of text are very confusingly placed!

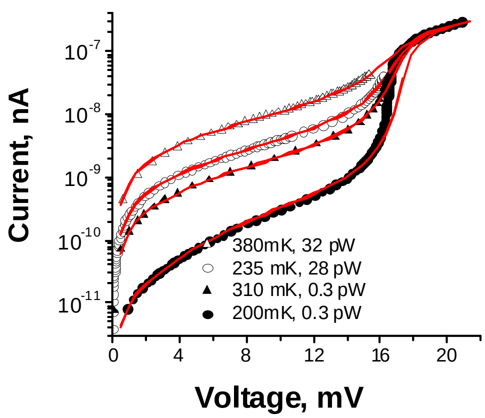
Reply: Corrected.

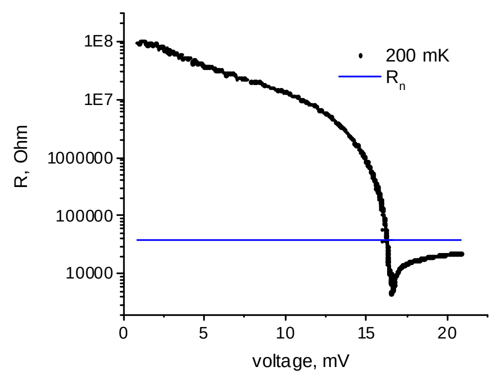
Comment:
14. Line 207: Is the abbreviation T_bb introduced somewhere?

Reply: Now it is introduced in the second paragraph of the section "Experiment".

Comment:
15. Line 226-230: figure 3-A. When determining the sample parameters, how was the asymptotical resistance (R in reference [8]) defined? Where the measurements extended to the asymptotic range?

Reply:
We add a figure with differential resistance on voltage in Supplementary materials and a description of the measurements of the normal state resistance.
R_n is measured above the critical temperature of aluminum. Also it can be measured below the critical temperature, but it requires voltages 3-4 times higher than the gap, because the IV-curve approaches the asymptotic line V = I * R_n very slowly. This is shown in the figures below.





Comment:
16. Equations (3): Have terms T_E, T_PH, \delta I etc. been introduced anywhere?

Reply:
We mean T_e and T_ph instead of T_E and T_PH. Now the capital indexes are removed from eqs. (3).
\delta I and other variables are introduced now after the eqs. (3).

Comment:
17. Lines 246-247: I think here is a typ of responsivity should be S_V not V_ND/S_V or did you mean V_ND/dP_Source? Also how is the responsivity defined? Is it a measured quantity or deduced from equation (1) of the article?

Reply: Yes, the responsivity is S_V. The sentence is rewritten.

Comment:
18. Lines 254-256: Here it is claimed that the amplifier noise dominates over NEP_eph and NEP_SIN. However, in figure 3-A the amplifier noise is smaller than these components. Please explain.

Reply:
This statement is valid for a single bolometer. For arrays, composed of many bolometers (192 in our case) the NIS noise can be higher than the amplifier noise in a certain voltage range. Therefore we change this sentence to the following:

The amplifier noise NEP_amp depends on a read-out type and for our room temperature amplifiers it has two terms: the current noise and the voltage noise.

Comment:
19. Lines 283-293: Is it true that if the IV-curves coincide, the amplifier and NIS-NEPs are about equal? Here the data are measured in two different temperatures and the temperature affects at least the responsivity of the device.

Reply:
Here we do not talk about NEP, which indeed is different because of the responsivity. We talk about the noise, which is a quantity that we measure directly in the experiment: the amplifier noise and SIN-noise are nearly the same in the case of coinciding IV-curves.

Comment:
20. Line 297-299: Figure 3-C does not demonstrate that photon NEP is larger than amplifier NEP even though that is claimed in the text. The amplifier NEP is not included in said figure.

Reply:
Our claim is different: the noise of the absorbed signal is higher than the total internal noise of the detector, including amplifier noise. Moreover, the corresponding total internal noise (including amplifier noise) NEP is compared in Figure 3-C with photon noise NEP. We have rewritten this sentence to make it more clear.

Comment:
21. Line 346: What is dark NEP?

Reply:
The dark NEP is the total NEP, when the incoming signal from the black body is zero (nearly zero) and only the residual background radiation from the sample holder and from the cryostat shields is present.

Comment:
22. Lines 350-360: The authors study a single bolometer. Is the point to demonstrate the ultimate limit of a device? Can a single bolometer ever be used to measure anything practical?

Reply:
Yes, it can be used, it depends on the working power range. For example, in our recent paper Appl. Phys. Lett., **110**, 162603 (2017) we have investigated the receiving system for Boomerang mission, where only 6 bolometers were used to match load power/NEP requirements.

Comment:
23. Figure 4: The NEP_amp in the legend of both figures indicates that this component comes from the same source. Change the legend 4-B to NEP_amp,cold etc.

Reply: Yes, thank you, we have changed it.

24. Figure 4: Is the difference is figure A and B only the difference in simulation voltage (and different amplifier)? This is not clear from the text.

Reply: The difference in A and B is the amplifier noise and the phonon temperature of the cryostat. Added to the text.

Comment:
25. Lines 411-413: Incomprehensible text.

Reply:
Yes, thank you, we have changed to: For example, in TES with a spider-web membrane, the absorber volume is usually of the order of 0.01 mm3, while the CEB absorber volume is only 0.02 um3

Comment:
26. Lines 476-477: Authors claim that the quasiparticles are not a (considerable) problem in their system. I noticed that this is studied by parameter \beta in Methods. Maybe add a mention of this. Also, the problems from quasiparticles depend highly on geometry and the geometry can be much bigger problem than the operation point. Maybe comment on that.

Reply:
Indeed the geometry of the electrodes is crucial for heating of the superconducting electrodes by the quasiparticles. In our samples we manage to decrease the heating from quasiparticles to low values (corresponds to \beta = 0.06) by making the double stock from the tunnel junction to the antenna, as shown in Fig.1-B. The problem of overheating arises at high voltages (near the gap), where our model is not very accurate. The accuracy (and at the same time the complexity) of the model can be increased by taking into account a spatial dependence of the temperature in superconducting electrodes. However, since we work below the gap, this modification is not necessary for us.

Comment:
27. Lines 437-490: Is the bolded list of differences between CEB and CP really necessary? It is good to discuss these things but is it necessary to highlight this over, say differences between CEB and KID or TES?

Reply: This part has been rewritten as a text and slightly shortened.

Comment:
28. Lines 510-511: How much lighter and cheaper is a He3-pot compared to dilution refrigerator? That is of course the first step towards the higher operation temperatures, but is increase from 20 mK to 300 mK world changing achievement?

Reply:
We don't know the cost of cryostats for space missions because it is very complicated is not developed finally for space operation. For example, the ground-based laboratory dilution cryostat (down to 10 mK) is at least twice more expensive than He3 cryostat (down to 300 mK).

Comment:
29. Line 516-518: How is developing an on-chip refrigerator relevant to this paper? Especially as the authors have claimed above that CP is much worse way to do thing compared to CEB.

Reply:
We mean the internal cooling of the absorber, utilized in CEB:

We are developing on-chip refrigerator, utilizing the electron self-cooling of the absorber.
Now we have shortened this part of the text, replacing it as:
This study suggests that CEBs with internal self-cooling are potential candidates to form the basis of a core technology with excellent parameters for advanced radio astronomy projects that must avoid dilution refrigerators.

Comment:
30. Methods, lines: 544-555: what is P_S? It is explained in reference [16] but should also be elaborated here! Where does the Joule heating come from? Heating due to resistivity of the absorber?

Reply: P_S is a power flow from back tunneling of quasiparticles in the superconducting electrode and absorption of phonons emitted by quasiparticle recombination. Joule heating is due to the resistivity of the absorber. Added into the text.

Comment:
31. Supplementary Note 1: Where does G_cool come from? Is it P_cool/\Delta T?

Reply:
G_cool = dP_cool/dT is the cooling thermal conductance of the SIN junction. Inserted into the text.

Comment:
32. Supplementary Note 1: Where do the time constants come from? Please add a reference.

Reply: Added [8].

Comment:
33. Supplementary Note 1: What is gamma?

Reply: gamma is the electron specific heat. Added into the text.

Comment:
34. Supplementary Note 2: Please tell the spacing of the powers. Now only the maximum and minimum values given.

Reply:
Added to Fig. S.2 description: The power changes over three decades: from 0.001 pW to 0.01 pW with the step 0.001 pW, from 0.01 pW to 0.1 pW with step 0.01 pW and from 0.1 pW to 1 pW with step 0.1 pW.

Comment:
35. Eq. 5: S electrodes are finite connecting to normal metal antenna. What is the consequence of neglecting spatial dependency in Eq. 5?

Reply:
Equation 5 includes the effective volume of superconducting electrodes, which is a fitting parameter. This parameter allows us to some extent to take into account the geometry of the electrodes, although it is not quite accurate (see the difference between the fit and the experiment at high voltages near the gap in Fig.3-A). With spatial dependence taken into account, the fit could be more accurate at high voltages. However, since the operation point is usually taken at lower voltages (2/3 of the gap), we did not try to extend the heat balance model above the gap.

Comment:
36. Please note that it is quite tedious to read the left column of the text as the line numbers of the right column are attached to it. For the referees' sake please fix this in the next round.

Reply: Fixed.