# SINIS Detectors: 30 Years of Achievements and Delusions

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***Abstract*—Superconductor-Insulator-Normal metal-Insulator-Superconductor (SINIS) structure with NIS tunnel junctions is a generic element for Andreev bolometers, normal metal hot electron bolometers, cold electron bolometers, electron coolers, cryogenic thermometers, etc. Past 30 years such devices intended mainly for microwave detection were developed both theoretically and experimentally. Some of results and conclusions are contradictive. Here we briefly review main experimental results and possible mechanisms of SINIS microwave detectors operation, influence of electron cooling, normal metal traps, nonequilibrium effects, quantum absorption and bolometric absorption, energy dissipation by phonons and electrons. Crucial issue for practical detector is proper integration with planar antenna array that determine coupling efficiency, beampattern, bandwidth. We compare two main approaches with modelling of infinite array with periodic boundary conditions and modelling of the entire moderate array. Comparison with experiments support the approach with modelling of the whole array and taking into account the different boundary conditions between adjacent antennas. Correct experimental study requires cryogenic bandpass filter and integrating cavity.**

***Keywords*—microwave detectors, NIS junctions, integrating cavity, SINIS detectors, planar antenna arrays**

## I. INTRODUCTION: SINIS MECHANISMS

A kick-off publication about proposed hot-electron microbolometer with NIS junction from 1993 [1] predicted voltage responsivity of $10^9$ V/W and noise equivalent power NEP=$3*10^{-19}$ W/Hz$^{1/2}$ that was measured by dc heating of normal metal absorber at an operating temperature of 100 mK. This estimation was very inspiring and later several attempts were made to measure optical response of such so-called Andreev bolometer at 300 GHz [2]. Surprisingly, the optical performance was much worse: dV/dP=$10^6$ V/W and NEP=$10^{-14}$ W/Hz$^{1/2}$. The explanation of contradiction was given in 2000 by I. Devyatov who pointed that aluminum Andreev contact is transparent at frequencies over 70 GHz. Perfect way to overcome such obstacle by replacing Andreev contacts by NIS tunnel junctions was proposed in 2001 by K. Likharev. This concept was proved experimentally in [3] with dV/dP=$0.4*10^9$ V/W and technical NEP=$10^{-17}$ W/Hz$^{1/2}$ limited by readout electronics. The next step was related to demonstration of electron cooling in [4]. As a consequence, a concept of cold electron bolometer was proposed in [5]. The actual role of electron cooling and corresponding suppression of current responsivity was studied in detail in [6]. It was concluded that the cooling of electrons alone does not provide the same responsivity as the cooling of the detector as a whole. Direct experiment does not support earlier hypothesis that without decreasing the phonon temperature of the SINIS detector, it is possible to achieve optimal responsivity. This statement is clear proved by expression from [7] for $NEP^2=10k\Sigma\nu(T_e^6+T_p^6)$ in which $T_e$ electron temperature, $T_p$ phonon temperature, ν volume, k, Σ constants. Phonon cooling requires dilution cryostat or adiabatic demagnetization refrigerator.

Using 3He sorption cryostats is not enough, and electron cooling does not help for achieving ultimate performance. One more point of contradictions is the mechanism of current response. Initially SINIS detectors were treated as bolometers in which the incoming radiation is completely absorbed in normal metal, that leads to temperature increase, and this increase is readout by NIS thermometer. Later in [8] it was developed more correct theory of quantum response. It was shown that for one absorbed photon with energy hf it is possible to detect up to hf/kT electrons. Estimation of current responsivity is based on nonequilibrium electron and phonon distribution functions and mechanisms of quantum absorption. Such quantum absorption with electron multiplication was experimentally demonstrated in SINIS structures with suspended absorber [9] with measured quantum efficiency of 15 electrons for one absorbed photon at 350 GHz. Important problem for any superconducting detector is overheating of superconducting electrodes and attempts to create traps for hot quasiparticles by attaching a normal metal layer. Simple solution by directly connecting such trap to superconductor is not realistic because it leads to suppression of superconductivity and heat sink is low due to Andreev reflection [10]. Proper way of arranging of normal metal trap is via high transparence tunnel junction. Such kind of

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tunnel-junction traps was studied in [11]. It requires two separate processes for NIS junction oxidation, high oxidation for SINIS detectors and coolers with about 1 kΩ/μm$^2$ and low oxidation for NIS traps with few 10 Ω/μm$^2$ resistivity. In more detail the principle of operating of SINIS-detectors are presented in [12, 13]

## II. INTEGRATION WITH PLANAR ANTENNAS AND MATCHING ELEMENTS

SINIS receiving structure is a wideband detector without any selectivity to incoming signal and its polarization. But using different antennas and matching structures it is easy to choose required frequency band.

### A. *Single antenna design*

Different planar antenna types were used depending on required frequency band and bandwidth. Among them we can mention log-periodic antenna for wide bandwidth, and for narrow-bandwidth twin-slot, twin-dipole, finline, L-shape, etc., (examples of SINIS detectors integrated with different single antennas are presented in Fig.1). Any planar antenna does not provide perfect matching SINIS detector to the incoming beam and require some kind of beam correction like immersion lens with counterreflector, or waveguide horn. Both options were tested in our experiments.

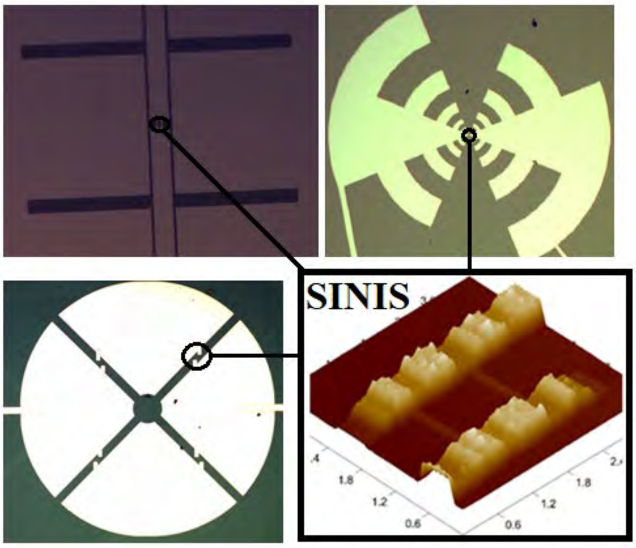


Fig.1. Twin-slot, log-periodic, annular ring antennas with SINIS detectors

### B. *Matrices of antennas*

Single detector has rather low saturation power and arrays of such antennas can be applied to increase dynamic range. In the case of voltage readout two-dimensional series array of cross-slot antennas were tested in experiments [15]. Example of dipole series array and circular antenna array are presented in Fig.2. The "classical" way is to use half-wave antennas as a unit cell of matrix. But another way is to construct array from electrically small antennas like metasurfaces. In this case, we have a more compact matrix with a large number of elements that can be placed directly into the waveguide [see. 14].

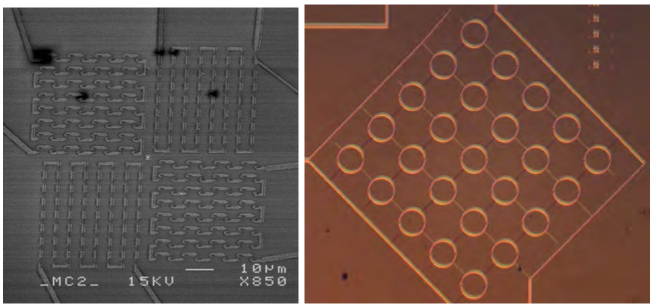


Fig.2. Series arrays of dipole antennas for two polarizations (left) and half-wave circular antenna array (right).

### C. *Silicone Lense*

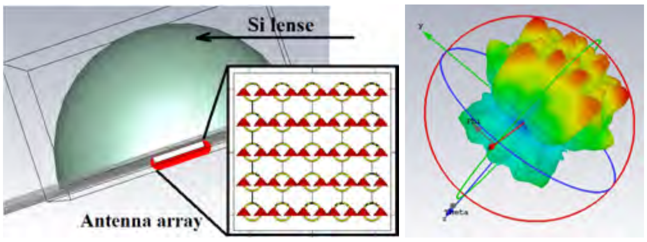
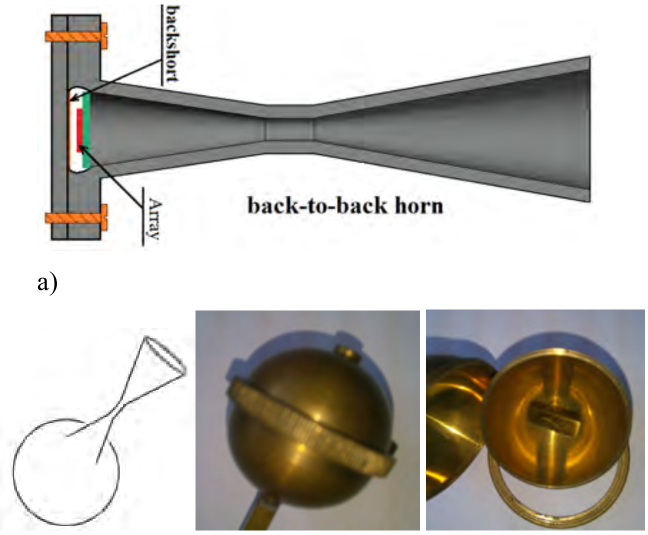


Fig. 3. Modeled project and calculated far-field beampattern of half-wave antenna array on silicon immersion lens.

### D. *Back-to-back horn and integrating cavity*

In the case of rather big array we use waveguide design in the shape of back-to-back horn. Schematic view is presented in Fig.4. Incoming radiation is first concentrated and fed to narrow circular waveguide, and then illuminate the wafer with antenna array and counterreflector (backshort).

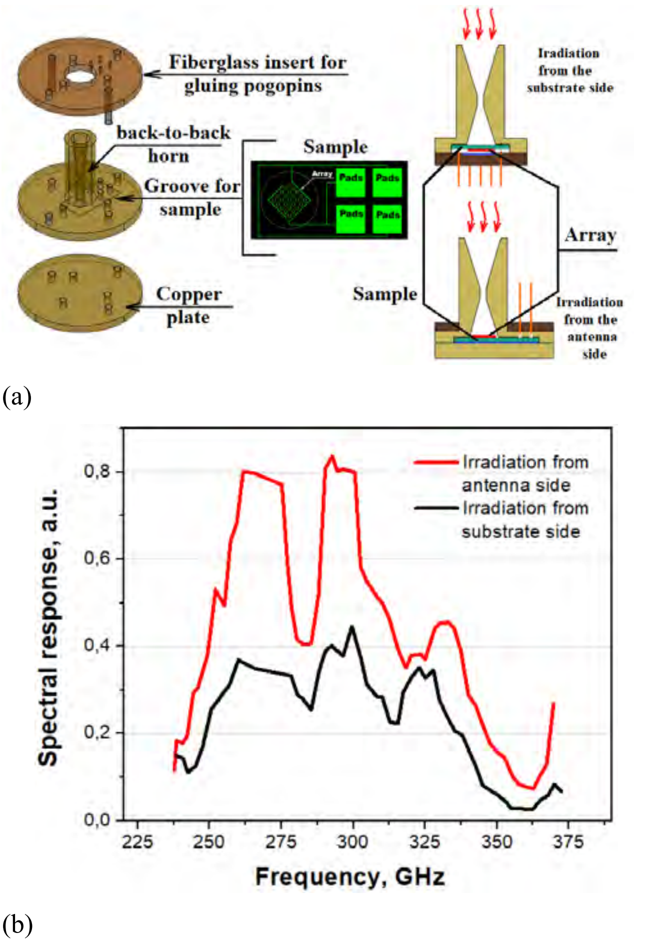


a)

b)

Fig. 4. Schematic view of back-to-back horn (a) and example of integrating cavity.

For such back-to-back horn we discovered that illumination from the antenna side is more efficient compared to popular way of illumination from the substrate side that is natural for immersion lens option (schematic image and results of measurements from [16], see Fig.5).



(a)

(b)

Fig.5. Schematic image (a) and results of measurements (b) for receiving array that were irradiated from the antenna and from the substrate side.

Additional method for improving of spectral response of receiving array is to use antireflection coating. As example for 350 GHz array it is possible to use 50 μm kapton (the results of measurements of matrix with/without such coating see in Fig. 6).

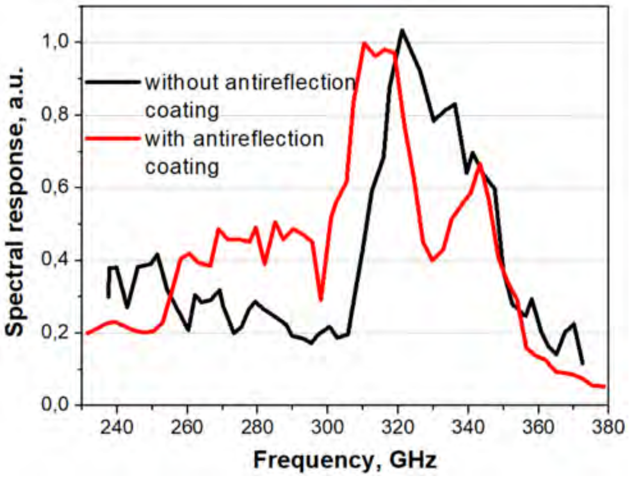
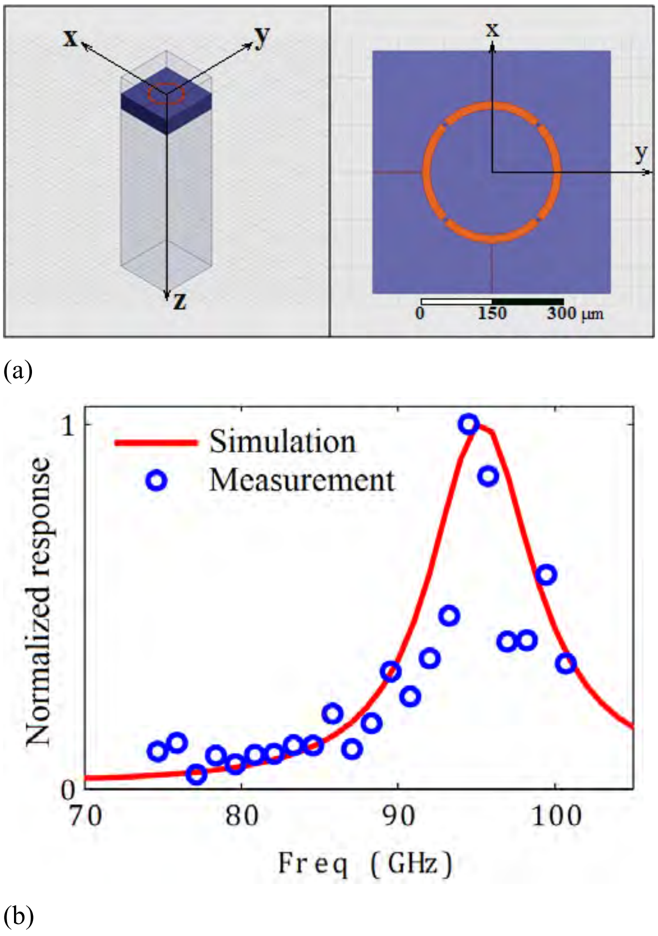


Fig.6. Results of experimental measurements of annular antenna array facing radiation from substrate side with and without antireflection coating

## III. MODELLING OF ANTENNA ARRAYS

Popular software tools like HFSS or CST provide convenient tutorials with examples for calculation of periodic arrays like quasioptical filters. It presumes periodic boundary conditions for infinite two-dimensional array. If losses of absorption are low, such approach can bring quick and reasonable results for spectral characteristics, beampattern and attenuation. Earlier we numerically simulated low-pass, high-pass, band-pass filters and obtained results were in reasonable correspondence with experiment [15, 17]. The conditions for calculation become quite different if each element contains absorber and provide moderate losses. This makes periodic boundary conditions not applicable, because phases at the boundaries between adjacent elements become indefinite. The only way to correctly model electrodynamics of such lossy array is to simulate the whole moderate matrix with all involved ports. Such calculation can be hundred times longer compared to simplified case of periodic infinite array, but it provides more realistic results. One important remark: periodic infinite array simulates phased array and its beampattern with sharp main lobe, and finite array of weak coupled elements in general demonstrate beampattern similar to that of single antenna. In detail the comparison of such methods of modeling for arrays and filters are presented in [14, 15]. Simple calculation of 90 GHz array and schematic project from [18] are presented in Fig.7. In contrary the same results but for full array are presented in Fig. 8.



(a)

(b)

Fig.7. Simulation (project – (a) and results – (b)) of infinite 90 GHz array of ring antennas from [18].

Experimental curve was obtained in cryostat with optical window and cold band-pass filter in front of matrix. Without such filter the sample is overheated and saturated by the incoming background radiation at room temperature.

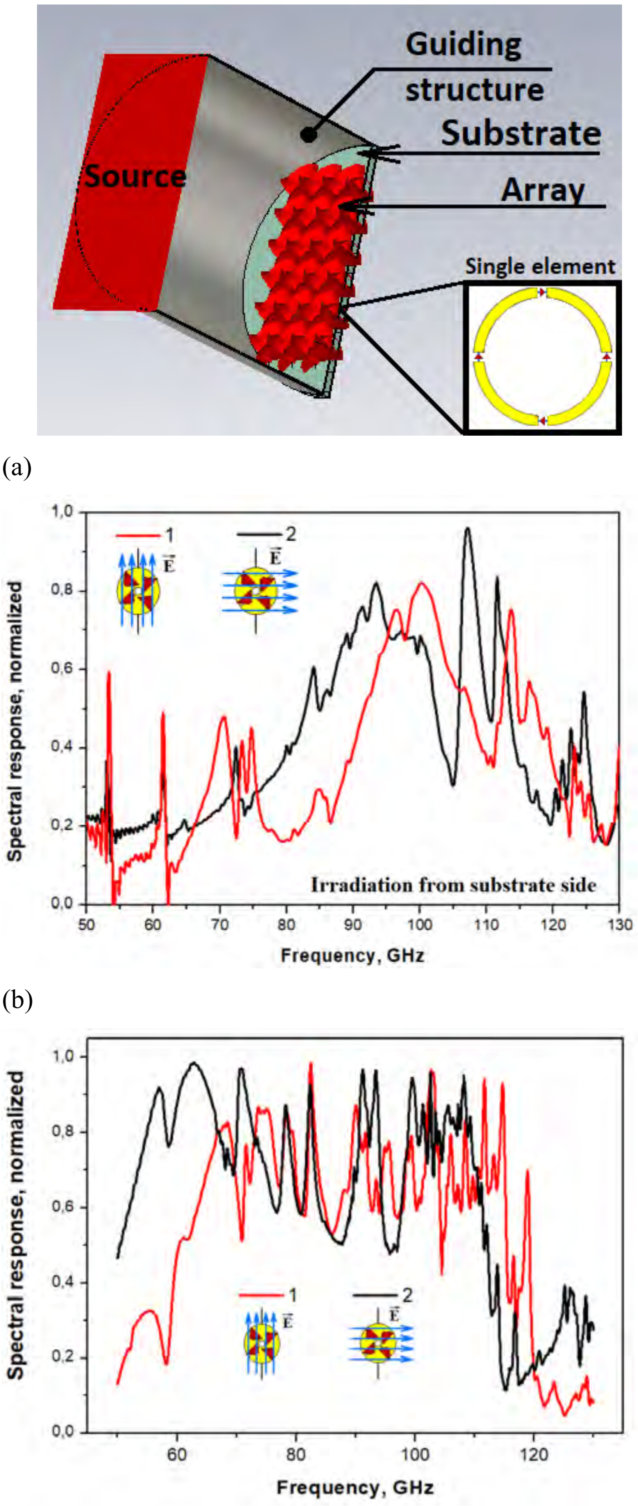


Fig.7. Modeled spectral response of 90 GHz array, the calculation was done for full array: (a) – irradiation from substrate side; (b) – irradiation from antenna side

Presented results of modelling and experimental studies of spectral characteristics of antenna arrays with SINIS detectors provide the practical way of designing for such receivers.

Another possible way is to use phased arrays to form a narrow-band radiation pattern. However, a phased array is a very complex set of microstrip lines and adapters that reduce all signals to a single point.

## IV. CONCLUSION

Here we briefly list initial delusions and final solutions obtained in the development of SINIS microwave detectors during past 30 years (see. Table 1). In spite of contradictive theoretical models and methods of numerical modelling, SINIS detectors demonstrate in experiment optical NEP down to $10^{-19}$ W/Hz$^{1/2}$ that makes SINIS detector competitive to other cryogenic detectors like Transition Edge Sensors (TES) and Kinetic Inductance Detectors (KID) bolometers at operation temperature below 100 mK.

TABLE 1.

| **Delusions** | **Solutions** |
|---|---|
| Andreev mirrors for thermal insulation of absorber from superconducting electrodes | Tunnel junctions with barrier height over the photon energy |
| Bolometric response, thermalization of energy, Fermi distribution, electron temperature | Quantum absorption, Nonequilibrium distribution, quantum response with multiplication |
| Electron cooling to improve current responsivity | Not applicable, suppress current response and increase shot noise. Phonon cooling is crucial |
| Direct contact normal metal traps to cool down superconducting electrodes | Transparent tunnel contacts and increasing volume of superconductor. |
| Quasioptical matching of planar antenna with immersion lens | Back-to-back horn and integrating cavity for proper beam and impedance matching |
| Antenna array with SINIS detectors can perform as phased matched array | Bolometer array is weakly coupled, should be simulated as a whole circuit with all available ports |
| Matrix can be irradiated from substrate side | Efficiency of irradiation from antenna side with counterreflector at the substrate side that mimic integrating cavity |
| Absorber on the substrate | Suspended absorber |

Without taking into account the listed sources of errors it is easy to underestimate the actual bandwidth of receiver and as a result to overestimate sensitivity. Calculation of performance with equilibrium electron temperature as main parameter is not adequate, it is necessary to apply kinetic equation for Nonequilibrium electron distribution function as in [8].

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