High-Gap Nb-AlN-NbN SIS Junctions for Frequency Band 790–950 GHz

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***Abstract*—We have designed, fabricated, and tested superconductor–insulator–superconductor (SIS) mixers based on Nb/AlN/NbN twin tunnel junctions for waveguide receivers operating in a frequency range of 790–950 GHz. Electromagnetic simulations and measurement results of the mixer performance are presented. The junctions have a high gap voltage of 3.15 mV and a high current density of about 30 kA/cm^2, providing a wide receiver band, which was confirmed by Fourier transform spectrometer (FTS) and noise temperature measurements. The corrected receiver noise temperature varies from 240 K at low frequencies to 550 K at the high end of the band. The influence of the SIS junction heating on its characteristics has been studied and compared to another similar high current density technologies. The heating does not have a critical impact on the mixer performance.**

***Index Terms*—Heterodyne receiver, high-energy-gap junction, superconductor–insulator–superconductor (SIS), terahertz receivers.**

I. Introduction

IN 2006, the CHAMP+ heterodyne array [1] was installed on the APEX (Atacama Pathfinder EXperiment) telescope [2]. The array is composed of 14 pixels, divided into two subarrays of 7-pixels each, arranged in a hexagonal configuration. The radio frequency (RF) tuning range is 620–720 GHz for the 45-μm and 790–950 GHz for the 350-μm subarray.

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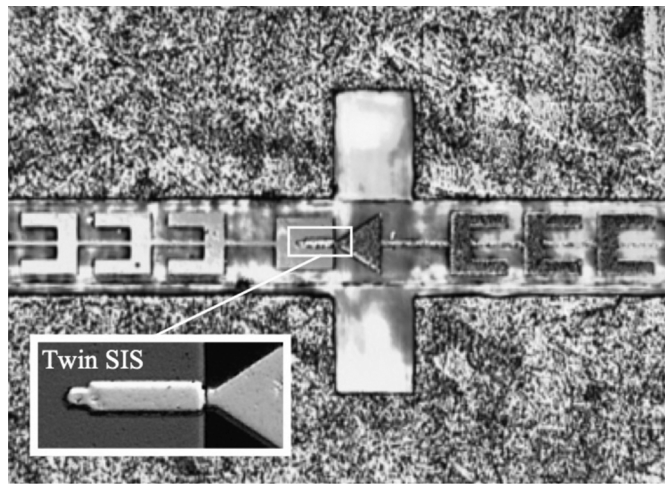

Fig. 1. Photograph of the SIS mixer (including the waveguide probe and filter structure) installed in a waveguide. The central part with SIS twin junction is magnified.

The low-frequency-band array is based on the state-of-the-art (at that time) superconductor–insulator–superconductor (SIS) mixers developed for the ALMA Band 9 receivers—a result of few years of research and development. For the high band mixers, on the other hand, a one-off design was made, without further modifications and iterations. Because of this, the performance of the high-band mixers was not optimized as far as the low band mixers, and can not be considered state of the art as compared with similar devices [3], [4].

Here we present our work on a new design of dual sideband high gap SIS mixers for 790–950 GHz, which are intended for upgrade of the existing CHAMP+ high-band array. An additional interest is to gain experience with high gap mixer technology for later use at frequencies above 1 THz, for example, in the Millimetron project [5] in the 950–1150-GHz range.

II. Design and Fabrication

In order to make a wideband receiver, we have used twin SIS junctions [6], [7] (each with an area of 0.5 μm^2), which are coupled by a waveguide probe to the E-field of a rectangular waveguide of 300 × 75 μm (Fig. 1).

We have developed an SIS mixer based on high-critical0current-density Nb/AlN/NbN tunnel junctions incorporated in a microstrip line consisting of a 300-nm-thick bottom electrode (ground plane) made of NbTiN and a 500-nm-thick top electrode made of Al [8]. The microstrip electrodes are separated by a 250-nm SiO_2 isolator. The Nb layer of the SIS junction is deposited on the NbTiN film, while the NbN layer is contacting the Al top electrode. The detailed procedure for the circuit fabrication is described in the following paragraph.

First, a NbTiN film was deposited on a fused quartz substrate at room temperature by dc sputtering with a NbTi target in a nitrogen atmosphere. For the NbTiN film, the critical temperature T_c was measured to be 14.1 K, and room temperature resistivity estimated to be 85 $\mu\Omega$·cm. The geometry of the ground electrode was determined by a reactive ion etching (RIE) process. The tunnel junctions were fabricated from a Nb/AlN/NbN tri-layer [8] with a normal-state resistance–area product $R_nA = 7\ \Omega \cdot \mu\text{m}^2$, which corresponds to a current density $J_c = 30$ kA/cm^2; the Nb and NbN layers have thicknesses of 100 nm. An AlN tunnel barrier was grown immediately after deposition of a 7-nm Al layer using an RF magnetron discharge. The samples were attached to the grounded substrate table, maintained at 20 °C, which was positioned directly above a 5-in Al magnetron RF source with a holder-source distance of 14 cm. For fabrication of the high-current-density tri-layer we initiated a plasma discharge using a power density of 0.7 W/cm^2 at a nitrogen pressure of 4.5 Pa; nitridation time was of about 40 s. Afterwards, the NbN was deposited by dc reactive magnetron sputtering at ambient temperature with 1.8 W/cm^2 power density using an Ar+9% N_2 gas mixture. Circular-shape junctions with an area of about 0.5 μm^2 were defined by deep ultraviolet photolithography. The SIS junctions were patterned from the Nb/AlN/NbN tri-layer by successive RIE of the NbN layer using CF_4, by RF sputtering of AlN/Al film in Ar plasma and finally by RIE of Nb layer using CF_4. The dielectric layer for junction insulation consists of 250-nm SiO_2, defined in a self-aligned lift-off procedure. At the final step, a 500-nm-thick top microstrip electrode made of Al was deposited by dc magnetron sputtering. Afterwards, the thickness of the quartz substrate was reduced to 40 μm by mechanical polishing.

In the past, Nb/AlN/NbN junctions with 0.5-μm^2 area fabricated on Si substrate with a 200-nm Nb layer and 100-nm NbN film demonstrated a gap voltage $V_g = 3.5$ mV and quality factor (ratio of the subgap to normal state resistance) $R_j/R_n > 30$ for $R_nA = 28\ \Omega \cdot \mu\text{m}^2$, while showing $V_g = 3.4$ mV and $R_j/R_n = 23$ for higher current density ($R_nA = 7\ \Omega \cdot \mu\text{m}^2$) [9], [10]. In contrast, the current SIS junctions with considerably thinner Nb electrodes (100 nm) and fabricated on the NbTiN film have $V_g = 3.15$ mV and quality R_j/R_n between 13 and 16 for $R_nA = 7\ \Omega \cdot \mu\text{m}^2$. We cannot explain the cause of such a decrease of the junction gap voltage yet. The V_g level is uniform over the wafer. Also, the yield of the working SIS junctions was high (>90%), although quite a variation of the junction area (of about 20%) was present.

The frequency of 950 GHz corresponds to 3.9-mV photon step, which exceeds V_g of both fabricated SIS junctions and classical ones with Nb electrodes ($V_g = 2.8$ mV). Consequently, the voltage range available for SIS mixer biasing is wider by about 0.7 mV for the described here mixers compare to Nb ones. It makes a big advantage for the mixer operation due to presence of problematic Shapiro feature right in the middle of the photon step (can be seen in the next section on Fig. 4).

Due to the high current density of the produced AlN barrier, the lower R_n gives a higher $1/R_nC$ ratio for the junctions (with C the junction capacitance), providing a wider receiver band. The design of tuning structure and waveguide mount is conceptually similar to original design of the CHAMP+ high band devices. The SIS junctions are embedded in a 4.5-μm-wide microstrip line with a 6.5-μm inter-junction distance, and coupled to the antenna by a 7 × 27 μm impedance transformer (see Fig. 1) tuned specifically for the high-current-density junctions.

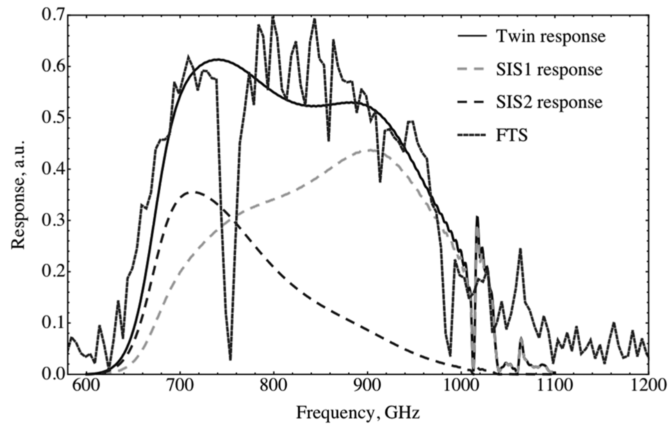

Fig. 2. Measured FTS response of the twin mixer—dotted line; simulations of the response—solid line; simulated response of each individual SIS mixer of the twin—dashed lines. Water vapour absorption lines are visible at 750 GHz and around 1 THz.

III. Measurements

A. FTS Results

In order to evaluate a wideband coupling of radiation to the SIS junction, a Michelson Fourier transform spectrometer (FTS) technique has been used. A wide band glow bar source was coupled to the Michelson interferometer, where SIS mixer was used as detector. A direct response of the SIS mixer current has been measured versus mirror position. A Fourier transform of the measured curve gives response shown in Fig. 2. In addition, electromagnetic simulations of the full mixer structure were performed using CST Microwave Studio. The calculated response of the mixer is presented on Fig. 2.

In the case of junctions with AlN barrier there are still uncertainties concerning the specific capacitance C_s of junctions as function of current density. In [11], it is assumed to be $C_s = 60$ fF/μm^2 for a critical current density of 56 kA/cm^2. On the other hand, it was measured as $C_s = 85$ fF/cm^2 for $J_c = 50$ kA/cm^2 in [12] and, estimated as $C_s > 100$ fF/cm^2 for $J_c > 20$ kA/cm^2 in [13] and [14]. To deal with this uncertainty, and, in addition, with variations in microstrip dimensions and junctions parameters due to manufacturing tolerances, a set of design modifications was implemented on the wafer.

The measured FTS response of the receiver is presented in Fig. 2 together with results of 3-D EM simulations on a full model of the mixer, including the tuning structure, the substrate and the waveguide backshort. According to the best fit between the data and the simulations, the specific capacitance is 80 fF/cm^2. The receiver response is wider than 200 GHz, however, it is clear that the design should be corrected to shift the

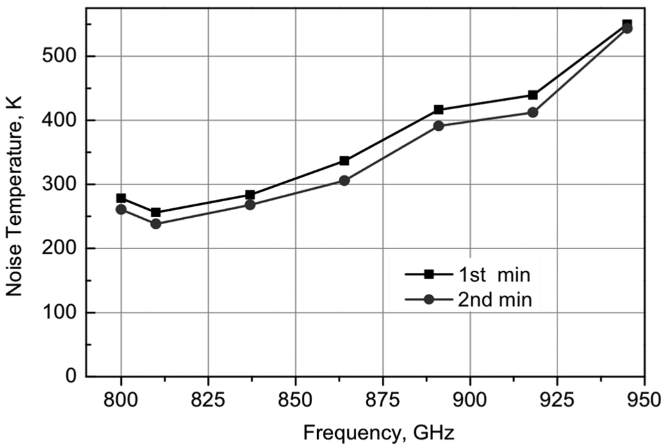

Fig. 3. DSB noise temperature, corrected for the loss in the LO insertion beam splitter, measured for the first (squares) and second (circles) minima of critical current suppression.

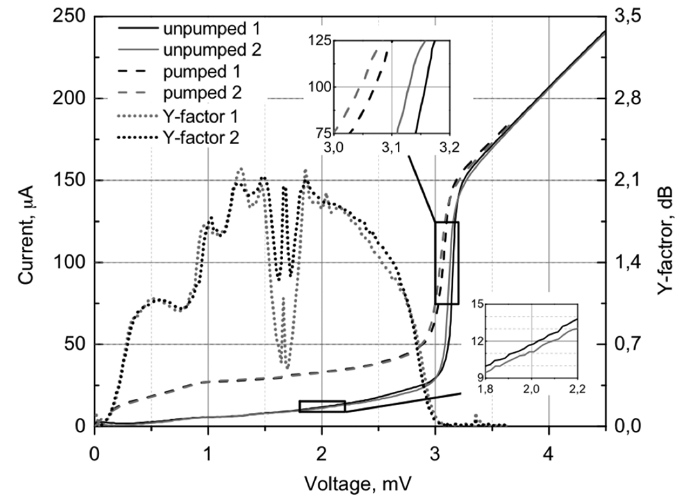

Fig. 4. I–V curves of one of the SIS junctions: "unpumped"—no LO power is applied (shown by solid lines), "pumped"—LO power providing an optimal T_n is applied (shown by dashed lines). The uncorrected Y-factor measured using 77 K/300 K loads is shown by dotted curves. Index "1" corresponds to the 1st minimum of the critical current suppression and related curves are grey; index "2"—to the second one and related curves are black. The insert at the top shows the details of the gap reduction due to junction heating by LO power and due to increased magnetic field. The insert at the right bottom corner demonstrates the sub-gap current variation around 2 mV for different minimums of the critical current suppression. The LO frequency is 810 GHz.

response to higher frequencies for better coverage of the desired 790–950-GHz range. The twin junction design clearly helps to widen the bandwidth, as can be seen in the distribution of the energy between the junctions (dashed curves on Fig. 2).

B. Noise Temperature

Noise temperature has been measured by Y-factor method using room temperature (300 K) absorber as hot load and absorber immersed in liquid nitrogen (77 K) as a cold load.

The results of the noise temperature T_n measurements are depicted in Fig. 3. The data is corrected for the 88% transparent 12-μm mylar beam splitter used for LO injection. Each point on the graph represents the DSB (dual sideband) noise temperature averaged over a 4–12-GHz intermediate frequency band. For the best junctions, the T_n level is about 230 K at low frequencies, and it goes up to 550 K at high frequencies. The presented frequency range is limited by the LO. Nevertheless, the noise temperature has been measured at 680 GHz and 720 GHz using a different LO, yielding values of 900 K and 350 K, respectively, and confirming an extremely wide mixer range (exceeding 200 GHz). In general, the measured T_n is in good agreement with the FTS data on Fig. 2.

The critical current suppression of twin SIS mixers of submicrometer junction area can be a problem due to shape and area difference between the junctions. For better suppression, it is preferable to use the second or even the third minimum of the critical current suppression curve (Josephson current versus magnetic field), since these minima are typically shallower than the first. However, it is known that a too-high magnetic field reduces the gap voltage V_g and can even decrease the response of the mixer at high frequencies [15]; both effects have a negative influence on the mixer performance. Our mixers have similar size and require about the same magnetic field level for critical current suppression. Nevertheless, in contradiction to results in [15], for our mixers, the second minimum not only provides a better critical current suppression compared to the first one (smaller Shapiro features for the Y-factor measurements, see Fig. 4), but also gives a 6% lower T_n (see Fig. 3). The reason is in high T_c of the NbTiN film and the influence of the H-field on the film surface impedance takes place at frequencies above the mixer range. It is confirmed by the observation that the FTS response does not degrade at all for higher H-fields, in contrast to, e.g., [15]. An additional T_n improvement is probably related to the reduction of the subgap current for higher H-fields (about 5% at 2 mV as shown in Fig. 4). The subgap current decrease seems to be caused by better suppression of the Josephson current.

The noise temperature for the third minimum was not measured because the critical current suppression was not stable there. The critical current versus H-field dependence $I_c(H)$ was not to be smooth above the second minimum, but showed sharp current jumps, as if the junction switches back and forth (sometimes with hysteresis) between different $I_c(H)$ curves. This behavior, which we have observed before for some high-current-density AlN-barrier mixers with both Nb electrodes produced for ALMA Band 9 receivers, was determined to be junction-related. Most likely, it is related to flux trapping or inhomogeneous distribution of the supercurrent close to the junction, leading to local field-dependent suppression of superconductivity.

C. Heating of the Junctions

With the choice of the Nb/AlN/NbN technology for the SIS junction fabrication with the NbTiN/SiO_2/Al three-layer for the embedding microstrip circuit, we expected some extra heating of the SIS function similar to one described in [16], [8] and caused by trapping of thermal electrons in the Nb layer by two higher-gap superconductors (NbTiN below and NbN on the top after a thin AlN barrier). In this case the charge would be transported from the Nb layer junction into the NbTiN and NbN, while the the energy transport would be blocked (a process known as Andreev reflection [17]) causing local heating of

TABLE I
COMPARISON OF JUNCTION HEATING BY LO SIGNAL FOR DIFFERENT MIXER TECHNOLOGIES

Name, (range, GHz)	SIS microstrip	Area, μm^2 *mixer type*	J_c, kA/cm^2	dV_g, mV	dV_g^*, mV
ALMA B9 Type1 (600-720)	Nb/AlN/Nb $Nb/SiO_2/Al$	0.25 *single*	56	0.03	0.06
ALMA B9 Type 2 (600-720)	Nb/ Al_2O_3/Nb $Nb/SiO_2/Al$	0.25 *single*	30	0.01	0.04
ALMA B10 (787-950)	Nb/ Al_2O_3/Nb $NbTiN/SiO_2/Al$	0.86 *twin*	10	0.06	0.21
CHAMP+ Type1 (790-950)	Nb/AlN/NbN $NbTiN/SiO_2/Al$	0.5 *twin*	30	0.1	0.2
CHAMP+ Type2 (790-950)	Nb/AlN/Nb $NbTiN/SiO_2/Al$	0.5 *twin*	21	0.05	0.14

"ALMA B9 Type1" corresponds to ALMA Band 9 SIS mixers with Al_2O_3 barrier; "ALMA B9 Type2" - Band 9 mixers with AlN barrier (data is taken from the lab measurements of cartridges delivered to ALMA); "ALMA B10" – ALMA Band 10 SIS mixer [18]; "CHAMP+ Type1" – high gap SIS mixer described in this paper, "CHAMP+ Type2" – copy of previous one, but with Nb layer instead of NbN to avoid the heating effect.

Here dV_g^* is a dV_g normalized to area of 1 μm^2 and to the current density J_c of 30 kA/cm^2. The area is given per individual SIS junction, in a twin there are two of them.

electron gas. Actually, although not shown here, for special test SIS junctions of 5 μm^2 area, the unpumped I–V curves have backbending, which is not the case for mixers corresponding to Fig. 4 due to much smaller area. The backbending and RF-power-dependent gap depression (see Fig. 4) could be explained by the Andreev reflection [16]. On another hand, in our case, the electron assemblies of the Nb and NbN layers are separated by the barrier and can be biased relative to each other by the bias voltage. It will change the transport condition for heat electrons in Nb layer and, basically, should cancel the Andreev reflection in dependence on bias polarity. That should provide asymmetry in the IV curves, which is certainly not the case, because they were measured to be perfectly symmetrical. As result, heating seems to be related not to Andreev reflection but to resistive properties of the mixer layers.

The gap voltage is reduced by $dV_g \approx 0.1$ mV for the LO power level giving the best noise temperature (see curves "pumped" compared with "unpumped" on Fig. 4, also in the insert). A comparison of this result to similar mixer technologies, both with AlN and A_2lO_3 SIS insulator barriers, is represented in the Table I (here our high gap mixers are called "CHAMP+ Type1"). For the small dV_g levels that we observe, we can assume that dV_g scales both linearly with the junction area and with the current density J_c (i.e., it scales with the total current). With this correction, shown in Table I by dV_g^*, the difference in heating between high gap technology and the others becomes smaller. Despite the expectation of heating due to the trapped hot electrons, one can see that the dV_g level of our device is not dramatically different from the ones without trapping mechanism.

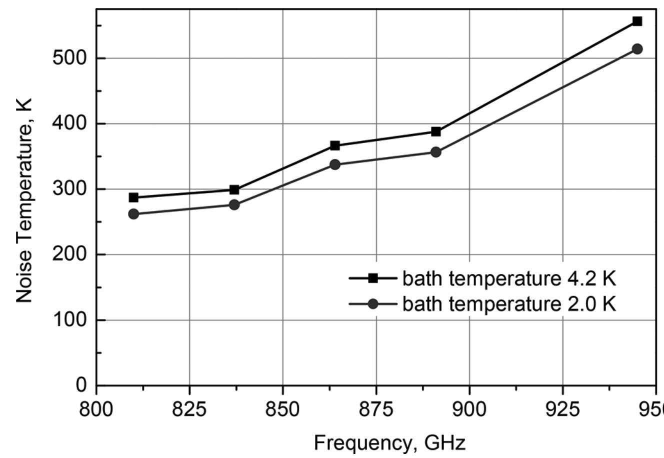

Fig. 5. DSB noise temperature, corrected for the beam splitter loss, measured at a bath temperature of 4.2 K (squares) and 2 K (circles).

To have an additional estimation of the heating effect in the high-gap mixers, we have fabricated SIS mixers by the same technology but with the NbN layer replaced by a Nb layer. These devices are presented in Table I as "CHAMP+ Type2". The difference in dV_g, after normalization on the current density J_c, is only 25%, showing that contribution of the NbN layer in junction heating is more than for Nb, but it is not a real bottleneck. This difference seems to be related to the difference in thermal conductivity and RF electrical resistivity of the Nb and NbN films.

It is interesting to mention that the optimal pumping level (ratio of the LO induced current to the gap current Ig) is only 16%–18%, which is lower than typical 20–25% for the regular single junction SIS mixers. It can be explained by unequal LO pumping of the individual SIS junctions of the twin mixer. The same effect is seen in other twin SIS junction structures, e.g., [18].

Eventually, due to the high V_g, the reduction of the photon-assisted tunneling step by $2dV_g$ is not very critical for the operation of the mixer, because, even for the highest frequency of 950 GHz, the step is reduced only from 2.4 to 2.2 mV, keeping the optimum bias point far away from V_g.

To estimate the deterioration of the noise temperature T_n due to heating of the junction, we have measured it at lower bath temperatures. By cooling down the mixer to a temperature of 2 K, V_g was increased by 0.1 mV and thereby compensating the gap reduction caused by the LO power, again at the optimal pumping level. In this case, the measured noise temperature is 10% less than at 4.2 K (see Fig. 5).

However, we should keep in mind that this measurement gives only a rough estimate, because, although the average pumped gap value at 2 K comes out the same as the unpumped one at 4.2 K, the temperature increase of the SIS electrodes may be different in both situations. For a 2 K bath temperature with applied LO power, the NbN energy gap still corresponds to 2 K since that part is well-cooled through the Al layer, i.e., it is higher than at 4.2 K. On the other hand, the energy gap of the Nb layer is evidently reduced with respect to its value at 4.2 K (due to heating by the LO signal), since we still get the same average Vg. It should be mentioned that the subgap current around 2 mV was reduced by 10%–13% for a 2 K bath temperature, compared to 4.2 K, which is comparable to the T_n change.

IV. Conclusion

The measured noise temperature of the new high-gap junctions is already 10% better than that of the average existing CHAMP+ high-band mixers which are currently installed on the APEX telescope [1]. As demonstrated, the heating of the junctions is reasonably small, and the Nb/AlN/NbN SIS junction embedded in a NbTiN/SiO_2/Al microstrip circuit is a promising technology. In view of the extremely wide FTS response shown by the twin junction design, it becomes attractive to switch to a much easier-to-operate single-junction design, providing still sufficient bandwidth. The final goal is to reach the same, or even better, sensitivity as the state-of-the-art mixers for ALMA Band 10 [3], which still demonstrates approximately 1.5 times better noise temperature than the junctions presented in this paper. The difference can be caused by losses at high frequencies in the NbTiN and Al microstrip electrodes. The quality of these films should be checked by additional experiments. Also, the design of the mixer should be slightly modified to shift the response to higher frequencies.

In conclusion, the presented mixer technology, compared with Nb/AlO_x/Nb mixers, looks rather promising: 1) higher Vg provides 0.7-mV wider photon step for high frequencies (gives almost 1.5-mV-wide operating bias range for a frequency of 1.15 THz); 2) high current density allows to design a very wideband mixer; 3) the high T_c of the NbTiN film makes it beneficial to use the second minimum of the critical current suppression; and 4) the junction heating is not critical for the mixer operation.

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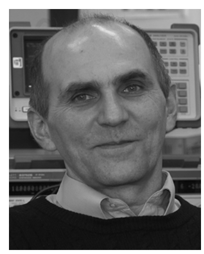

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