Emission of light and conversely rectification of an optical signal using an all-metallic electronic device is of fundamental and technological importance for nano-optics. However, despite recent experimental efforts in the development of electrically-driven plasmonic sources, the interplay between quantum transport and optics is still under debate. Here, we measure the photon-assisted current in a planar tunnel junction under infrared illumination. To address the microscopic mechanism at the origin of the optical rectification, we compare the photon-assisted current and the current-voltage characteristic of the junction measured on a voltage range much greater than $V_0 = \frac{hc}{2e\lambda} = 0.825$ V, previously unexplored. The experimental results do not agree with the theory based on the existence of a non-thermal distribution function corresponding to the exchange of energy quanta between electrons and photons. We show instead that the illumination power mainly goes into heating and that the rectification results from the tunneling Seebeck effect.
Recent years have seen tremendous progress in plasmonics and nanophotonics with the realization of optical antennas which can receive\(^{1-3}\) and emit radiation at optical frequencies\(^{4-12}\). It allows a subwavelength confinement of light as well as its enhancement inherent to the surface plasmon excitation. If plasmonic excitations are however generally obtained by optical excitations, the development of electrically-driven nanoscale plasmonic sources has attracted intense interest in recent years\(^{8-11}\), particularly for its potential across photocatalysis\(^{12}\). Electrical control offers much easier means and opportunities. In particular, surface plasmon sources based on inelastic electron tunneling (IET) in metal–insulator–metal junctions (MIM) have been known to emit radiation for a long time\(^3\), but they have gained an increased attention thanks to the recent report of an enhanced electron-to-plasmon conversion efficiency\(^8\), which makes them serious candidates as potential electronic drive for optical antennas. Two different processes related to photon emission in electron tunneling had been identified: (i) inelastic tunneling corresponding to photon emission in the barrier and (ii) hot electron decay where electron injected in the electrode excite surface electromagnetic resonances. According to the estimation of Persson and Baratoff most of the emitted light results from inelastic tunneling and the one due to hot electrons injection is mostly negligible\(^{14}\). In the following, what we will called abusively “hot carriers” will refer to carriers with a strongly non-thermal distribution function. These distributions will typically present “flat shoulders” induced by photons absorption. In terms of detectors, nanoantennas allow an efficient transfer of radiation into surface plasmons. Thus, if coupled with a nonlinear element, they can be used for optical rectification. One thus refers to rectenna: a nanoantenna converts the optical radiation into an ac voltage which is in turn converted thermal distributions\(^{25}\). As a result, our data are well described by the Tucker formula (TF): 
\[
\delta I(V_{dc}, V_{ac}) = \left(\frac{eV_{ac}}{2\hbar \omega}\right)^2 \left[I_0(V_{dc} + V_n) + I_0(V_{dc} - V_n) - 2I_0(V_{dc})\right],
\]  
(1)

where \(V_{dc} = \hbar \omega/e, \hbar \) is the Planck constant and \(e\) the elementary charge. The TF is the measurable quantity allowing to directly probe the out-of-equilibrium distribution function and the TF will confirm or deny the generation of hot carriers in the electrodes under illumination. Below, we will investigate the TF in a voltage range that has never been investigated for \(V_{dc} \sim V_{th}\), where the optical rectification is supposed to be strongly different from the classical one. This is technically demanding as it requires to be able to polarize a MIM junction with a voltage bias \(V_{dc} > V_{th} \sim 1\) V without deteriorating the device. We are not aware of previous work in this regime. To do so, we have chosen to perform the experiment on a robust Al/AlOx/Al tunnel junction at low temperature to prevent junction aging effects as experimentally verified in our previous works\(^{21}\). We use infrared radiation \(\lambda = 1550\) nm corresponding to \(\nu = 0.825\) V. We found that PAT in MIM junctions cannot be explained by the theory of quantum detection as expected by Eq. (1). Knowing that the Fermi-liquid theory gives lifetime of an excited electron of the order of \(\tau \sim \tau_e(n_e/\delta e)^2\), the lifetime of quasiparticles excited by optical photons is more than eight order of magnitude shorter than the ones excited by microwaves. For electrons with energy \(\delta e = eV_0 = 0.825\) eV above the Fermi energy, we estimate \(\tau \sim 100\) fs. This lifetime can only be accessed by time-resolved photoemission spectroscopy\(^{23,24}\). As a consequence, the tunnel spectroscopy under continuous wave illumination can hardly reveal non-thermal distributions\(^{25}\). As a result, our data are well described by thermal distribution functions characterized by a temperature in each electrode and highlight a tunneling Seebeck effect.

To increase the coupling between light and the tunneling current, we convert the far field radiation into a local electromagnetic mode of a surface plasmon polariton (SPP) resonance. We first show that the desired coupling is achieved by measuring angle dependence of the surface plasmon resonance by the photon-assisted current. We then measure the right and left hand sides of Eq. (1) independently. We discuss the validity of Eq. (1) in the optical regime by developing a theory using the Tien and Gordon\(^{20}\) and the Simmons tunnel barrier model\(^{26}\). In order to probe in more detail the interplay between illumination and the electron distribution in metallic thin films, we compare our measurement with the two possible senari: the hot carrier distribution functions characterized by a step like function at optical energies and the equilibrium distribution function at different temperatures.

Results and discussion
Sample fabrication and experimental setup. The sample is a 100 × 100 \(\mu m^2\) metallic cross-junction deposited on a standard microscope cover glass. The aluminum electrodes thickness is \(a \approx 8\) nm and the tunneling barrier is obtained by Al oxidation performed in a glow discharge. The \(I(V)\) characteristic fit\(^{26}\) enables to determine the barrier characteristics depicted in Fig. 1c: thickness \(d = 1.6\) nm, barrier height \(U_0 = 2.9\) eV and barrier asymmetry \(\Delta U_0 = -0.78\) eV. The asymmetry of the barrier although important for a symmetrical junction is related to the aluminum oxide growth\(^{27}\). The difference in thickness between the 2 electrodes has no significant impact on the optical simulations. A right angle prism is glued with a UV-curing glue on the rear of the glass to allow the SPP excitation by the incoming optical radiation in a Kretschmann configuration\(^{28}\) (see Fig. 1b). The experimental setup is shown in Fig. 1a. The junction
Photon-assisted tunneling at infrared frequencies. The responsivity \( R \) of a rectifier is given by the ratio between the photon-assisted current \( \delta I \) and the optical absorbed power \( P \). Let’s assume that optical excitation induces an ac signal of amplitude \( V_{ac} \) at frequency \( \omega \). The related ac current is given by \( I_{ac} = G(\omega)V_{ac} \) where \( G(\omega) \) stands for the conductance at frequency \( \omega \). In the classical limit of small ac excitation \( (\hbar \omega \ll eV_{dc} \text{ and } V_{ac} \ll V_{dc}) \), the conductance is associated to the adiabatic response of the \( I(V) \) characteristic \( G(\omega) = I'(V) = \frac{dI}{dV} \) and the time-averaged current is proportional to its second derivative \( \delta I = I''(V_{dc})\times V_{ac}^2/2 \). Surprisingly, this classical limit seems to account for the experimental results of Ward et al.\(^{30} \) out of its regime of validity \( V_0 \gg V_{dc} \). With the hypothesis that the optical absorbed power is equal to the electrical one \( P = G(\omega)V_{ac}^2 \), the responsivity can be rewritten by \( R = \frac{I'(V_{dc})}{V_{ac}} \) as for a classical diode. Following the same assumption and using the Tucker’s description of the electronic transport in a metallic tunnel junction at finite frequencies, the conductance is given by \( G(\omega) = \frac{\hbar^2}{2e^2}\frac{V_{dc}}{n} \frac{V_{dc}+V_0}{V_{dc}+V_0-V_{ac}} \) and the responsivity in the quantum regime reads\(^{18} \)

\[
R(V_{dc}) = \frac{1}{V_0^2} \frac{I_0(V_{dc}+V_0)+I_0(V_{dc}-V_0)-2I_0(V_{dc})}{I_0(V_{dc}+V_0)-I_0(V_{dc}-V_0)}. \tag{2}
\]

Figure 3 shows the experimental responsivity \( R^{exp}(V_{dc}) = \frac{\delta I^{exp}}{P_{abs}} \) measured as a function of the bias voltage for different laser powers at SPR. The absorbed power at SPR is proportional to the laser power: \( P_{abs} \approx 0.07P_{laser} \) (see Fig. 2a and Supplementary Fig. 4a). As shown in Eq. (2), the responsivity does not depend on the illumination power. The conversion efficiency of the metallic tunnel junction is independent of the incident optical power and acts as linear photon detector for the investigated power range \( P_{laser} < 100 \text{ mW} \). We estimate the maximal experimental responsivity at SPR: \( R^{exp}(V_{dc} = 1.7 \text{ V}) \sim 400 \text{ nA W}^{-1} \). By using the measured \( I(V) \) characteristic between \(-1.7 \text{ V} \) and \( 1.8 \text{ V} \) (see inset Fig. 3), we estimate the theoretical responsivity \( R(V_{dc}) \) between \(-0.88 \text{ V} \) and \( 0.97 \text{ V} \). We see in Fig. 3 that \( R^{exp} \) does not have the same voltage dependence (black dashed line) and is more than seven orders of magnitude smaller than the theoretical value given by

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Photon-assisted tunneling at infrared frequencies. The characteristics of the junction is measured using a standard four-point probe method simultaneously with the photon-assisted current. The current generated due to the radiation is given by a lock-in amplifier referenced to the optical chopper at frequency \( f_{chopper} \) ranging from 80 Hz to 900 Hz. The SPP mode is transverse magnetic. It is excited by a p-polarized light at the resonance frequency \( f_0 \) given by a lock-in amplification of the reference signal \( f_{chopper} \). The tunnel barrier is modeled by a trapezoidal barrier.
Validity of the Tucker formula. Equation (2) is convenient because it directly gives the photon responsivity of the junction from its electrical characteristics $I(V)$. However, this description is based on two strong hypotheses: (i) the photon-assisted processes can be described by an optical voltage biasing of the junction and (ii) the absorbed power is given by the electric resistance of the junction evaluated at optical frequency. Let us briefly show how to establish Eq. (1). The effect of voltage bias $V(t) = V_{dc} + V_{ac} \cos \left( \frac{2\pi}{T} t \right)$ due to the dc bias and the laser illumination is to shift adiabatically the Fermi sea of the upper reservoir sustaining the surface plasmon while the lower reservoir is grounded. The resulting time-averaged out-of-equilibrium distribution function $\tilde{f}$ in the upper reservoir is then given by the Tien-Gordon formula: 

$$\tilde{f}(\epsilon, T_0, V_{ac}) = \sum_{n=-\infty}^{\infty} j_n \left( \frac{V_{dc}}{V_0} \right)^2 f(\epsilon + n e V_0, T_0),$$

where $j_n$ is the $n^{th}$ Bessel’s function of the first kind and $f(\epsilon, T_0) = 1/(1 + \exp(\epsilon - e_F)/k_B T_0)$ is the Fermi–Dirac distribution with $e_F$ the Fermi energy and $T_0$ the electron temperature. The non-equilibrium distribution function reflects the fact that electronic states with energy $\epsilon$ are split into subbands with energies $\epsilon \pm n e V_0$ due to absorption/emission processes of photons at frequencies $\frac{eV_n}{k_B}$. Using a Landauer–Büttiker scattering approach, we express the time-average PAT current as 

$$\delta I(V_{dc}, V_{ac}) = \frac{e}{h} \int \left[ f(\epsilon - eV_{dc}, T_0) - f(\epsilon - eV_{dc}, T_0) \right] d\epsilon.$$

Using $\sum_{n} |j_n|^2 = 1$ and assuming that transmission is voltage independent $T(\epsilon, eV_{dc}) = \text{const}$, one deduces

$$\delta I = \sum_{n} \left| j_n \left( \frac{V_{dc}}{V_0} \right) \right|^2 I(V_{dc} + n e V_0) - I(V_{dc}).$$

If one only considers the one photon absorption/emission processes at energies $\epsilon (V_{dc} \pm V_0)$ ($V_{ac} \ll V_0$), Eq. (5) corresponds to Eq. (1) by retaining the lowest order terms in $V_{ac}/V_0$. Note that Eq. (4) is explicitly not gauge invariant. This hypothesis is valid in the microwave regime where the alternative electric field is well described by a voltage drop across the junction (one electrode is effectively grounded). However, it remains a strong assumption in optics where the lower electrode is not grounded at optical frequencies and the associated vector potential does play a role. In what follows, we focus on the experimental verification of Eq. (1). To do so, we probe $\delta I$ in a range of $\pm V_{exp} \simeq \pm 1$ V and the $I(V)$ characteristic in a range of $\pm (V_{exp} + V_0) \simeq \pm 1.8$ V. Figure 4 shows the PAT current measured by optically chopping of the laser beam at $\sim$120 Hz. The data are compared to the TF photon-assisted tunneling current $\delta I_{\text{Tucker}}$ given by Eq. (1). Note that this quantity is directly measured. The only free parameter is the optical voltage $V_{ac}$ which is adjusted with the slope of $\delta I_{\text{TAC}}$ at zero dc bias. We then deduce an optical voltage $V_{\text{Tucker}} \approx 1.52$ mV. This value is overestimated by more than four orders of magnitude in view of the laser power (according to Supplementary Fig. 4a, $P_{\text{laser}} = 53$ mW corresponds to $V_{ac} \approx 70$ mV). More importantly, equation (1) does not account for the
experimental data neither quantitatively nor qualitatively. As mentioned above, this equation assumes that tunnel transmission is voltage independent: $\bar{T}(e, eV_{dc}) = T_0(e)$. This is not the case at bias voltage of the order of the tunnel barrier height. Instead, the transmission $\bar{T}(e, eV_{dc})$ is calculated by modeling the junction by a trapezoidal barrier$^{36}$ (see the inset of Fig. 3 and Supplementary Note 2). A numerical evaluation of Eq. (4) gives a smaller but still unrealistic optical voltage $V_{dc}^{\text{Tien-Gordon}} = 0.48 \text{ mV}$. In conclusion, the fitting parameters using TF are not physical. Our experiment confirms that the description of the photon-assisted tunneling as an optical rectification cannot explain the photon-assisted processes in a tunnel junction. A more realistic description is to consider the Boltzmann equation (BE) describing electron dynamics in metallic systems$^{33}$.

**Hot-carrier vs thermal distribution.** The PAT current of Eq. (4) can be rewritten in terms of the deviation of the electron distribution from the equilibrium:

$$\delta I(V_{dc}, \delta f_{up}, \delta f_{dn}) = \frac{e}{h} \int dc T(e, eV_{dc}) \times \left[ \delta f_{up}(e + eV_{dc}) - \delta f_{dn}(e) \right],$$

(6)

where $\delta f_{up/dn} = f(e) - f(e, T_0)$ states for the deviation of the electron distribution from the equilibrium distribution at base temperature $T_0$. This steady-state non-equilibrium electron distribution function under continuous wave illumination is given by the master equation:

$$\left( \frac{\partial f}{\partial e} \right)_{e-ph} + \left( \frac{\partial f}{\partial e} \right)_{e-e} + \left( \frac{\partial f}{\partial e} \right)_{exc} = 0,$$

(7)

where $f$ is the electron distribution function. The first term stands for electron-phonon energy transfer between electrons and lattice, the second stands for electron-electron thermalization (characterized by an electron collision time of the order of few 100 fs) while the third term describes the excitation due to photon absorption in the contacts. The first two terms will mainly lead to an equilibrium distribution characterized by an effective temperature. The excitation term could, however, lead to the existence of a small fraction of "hot electron". We evaluate below what would be the effect of a "hot electron" distribution on the PAT. It can be evaluated by considering a detailed balanced equation and the Fermi golden rule (see Eq. 6 in “Methods”):

$$\delta f_{exc} = \frac{\delta f}{\partial e} = A_{exc} \left[ \sqrt{e - eV_{dc}(e)} (1 - f(e)) - \sqrt{e + eV_{dc}(e)} (1 - f(e)) \right],$$

(8)

where $A_{exc}$ is a constant proportional to the energy absorbed by electrons. In the relaxation time approximation for the electron-electron thermalization, we deduce the time-average PAT current of Eq. (4) due to hot-carrier contribution by considering the deviation of the electron distribution $\delta f_{up/dn} = \delta f(e, A_{up/dn}) \propto \sqrt{V_{dc}} \delta f_{up/dn}$, $A_{up/dn}$ is a constant proportional to the energy absorbed in the upper/lower electrode. It is convenient to characterize this amount of energy by expressing it in terms of equivalent temperature of excitation $\delta T_{exc}$. To do so, we consider a Fermi–Dirac distribution at $T_0 + \delta T_{exc}$ containing the same energy as the non-equilibrium distribution function:

$$\int e\rho(e) \left| f(e, T_0) + \delta f_{exc} \right| \, de = \int e\rho(e) f(e, T_0 + \delta T_{exc}) \, de,$$

(9)

where $\rho(e) \propto \sqrt{e}$ is the density of states of the free electron gas. Figure 5 shows the photon-assisted current $\delta f(\phi)$ as a function of dc current flowing through the junction biased between $-1.78 \text{ V}$ and $+1.84 \text{ V}$. It is mainly proportional to the current. Dashed blue line in Fig. 5 corresponds to the theoretical prediction given by Eqs. (6), (8). We clearly see that the proportionality cannot be explained by a hot-carrier distribution function. We fit $\delta I(V_{dc})$ by adjusting the absorption coefficients $A_{up} \sim 1.42 \times 10^{-8}$ and $A_{dn} \sim 0.69 \times 10^{-8}$ with an optimization software. Note that $A_{up} > A_{dn}$ in agreement with the fact that upper electrode experiences the field enhancement of the surface plasmon. They correspond to equivalent temperatures of excitation of $\delta T_{exc, up} = 0.30 \text{ K}$ and $\delta T_{exc, dn} = 0.15 \text{ K}$ respectively as described in Fig. 7 in the Methods. Even if this term leads to a Tien-Gordon-like distribution given by Eq. (3), the hot carrier distribution remains extremely small because of electron heating and heat leakage to the lattice as studied by Dubi and Sivan$^{30,33}$. Moreover, the equivalent temperature of excitation is smaller than 0.3 K and we see in the following that this temperature remains smaller than the temperature induced by the power absorption in the lead. It follows that the photon absorption mainly induces heating rather than generating hot carriers. In the following, we analyze the PAT current as resulting from two different thermal distributions in the contacts and can be refereed as the tunneling Seebeck effect$^{35}$. However, unlike the Seebeck effect which depends on the metallic density of states of the electrode materials, the tunneling Seebeck effect depends on the energy dependence of the tunneling transmission and so that on the nonlinearity of the $I(V)$ characteristic$^{36}$. The PAT current is then described by Eq. (6) with the deviation of the electron distribution $\delta f_{up/dn} = \delta f(e, T_{up/dn}) = f(e, T_0 + \delta T_{up/dn}) - f(e, T_0)$. $T_{up/dn}$ is the temperature of upper/lower electrode.
Figure 5 shows the proportionality between the photon-assisted current and the current. This proportionality is explained by differential heating between the upper and lower electrodes. Our data are in good agreement with the heating description (red dashed line in Fig. 5). We have checked that the PAT measured across the junction is one order of magnitude greater than the photon-assisted current in each electrode. The cross-geometry of the tunnel junction allows us to measure the photon-assisted current in the upper/lower electrode by using a current polarization of the upper/lower electrode. The power supply is connected on the VBG contact (resp. VB) to measure the upper (resp. lower) electrode (see Fig. 2) while the current amplifier is connected to the opposite side of the electrode. Inset of Fig. 5 shows the photo-assisted current measured in the two electrodes independently. This photon-assisted current is attributed to a variation of the aluminum conductivity. The Drude conductivity is indeed proportional to the relaxation time which depend on the temperature so that a laser induced temperature modulation will induce a conductance modulation. The energy and voltage dependent transmission T(ε, V) of the barrier is deduced from the fit of the I(V) curve. The fit of the curve \( \delta f^{(hh)}(T) \) gives \( \delta T_{\text{up}} \approx 3.22 \) K and \( \delta T_{\text{dn}} \approx 2.54 \) K. The temperature rise can be associated with the optical power absorbed by the electrodes. The junction in the Kretschmann configuration forms a well defined plasmonic multilayer stack and the absorbed power at the resonance angle \( \alpha_{\text{res}} = -39.7^\circ \) are evaluated to \( P_{\text{up}} \approx 265 \mu \text{W} \) and \( P_{\text{dn}} \approx 84 \mu \text{W} \), respectively (Supplementary Fig. 4b). We neglected the power leakage due to thermal conduction of the contacts and identify the absorbed power and the power dissipated to the lattice of volume \( V = a \times w \times w_{\text{beam}} \approx 5.2 \times 10^{-6} \text{ m}^3 \) where \( w_{\text{beam}} \approx 650 \mu \text{m} \) is the laser beam diameter. The temperature rise in the electrodes is thus estimated to

\[ \delta T_{\text{up/dn}} = \left( \frac{P_{\text{up/dn}}}{\xi^2} \right)^{1/5} \]

where the electron-phonon coupling constant in aluminum \( \xi \) is \( \approx 0.3 \text{ nW} \mu\text{m}^{-3} \text{K}^{-5} \). It gives \( \delta T_{\text{up}} \approx 1.7 \) K and \( \delta T_{\text{dn}} \approx 1.0 \) K. Note that the estimated temperature rise is slightly underestimated. It can be attributed to the value of the dielectric constant that we have considered knowing we consider here an unusual ultra-thin aluminum film. The photon-assisted tunneling is strictly speaking a thermo-assisted tunneling. Our measurement could also be sensitive to the variation of the electrode conductance due to their temperature modulation. Thanks to the cross-geometry of the junction, we have checked that this effect is negligible compared to the PAT measured on the junction. The inset of Fig. 5 shows that the photon-induced current in the electrodes is lower by more than one order of magnitude compared to the PAT current. The modulation of the light power by the chopper (laser on/off) induces a modulation of the resistance of the electrodes:

\[ R_{\text{up/dn}}^{\text{off}} = R_{\text{up/dn}}^{\text{on}} + \delta R_{\text{up/dn}}^{\text{on}} \]

When the electrode is voltage bias, this translates in a photon-induced current given by

\[ \delta I = I^{\text{on}} - I^{\text{off}} = -\delta R_{\text{up/dn}}^{\text{on}} I. \]

The inset of Fig. 5 shows that the photon-induced current in the electrodes corresponds to a relative increase of their resistance (\( \delta R > 0 \)) \( \eta_{\text{up}} = \delta R_{\text{up}} / R_{\text{up}} \approx (7.3 \pm 0.2) \times 10^{-7} \) and \( \eta_{\text{dn}} = \delta R_{\text{dn}} / R_{\text{dn}} \approx (3.6 \pm 0.2) \times 10^{-7} \). Using the Sommerfeld expansion in the electrical conductivity and assuming a linear dependence of the relaxation time, we expect a quadratic temperature dependence of the conductivity so that

\[ \frac{\delta \sigma}{\delta T_{\text{dn}}} \approx 2.0 \pm 0.3 \]

(see Supplementary Note 3). We then deduce a ratio \( \frac{\sigma_{\text{dn}}}{\sigma_{\text{up}}} \approx 1.4 \pm 0.2 \) which is consistent with the measured ratio \( \frac{\delta T_{\text{dn}}}{\delta T_{\text{up}}} \approx 1.27 \).

### Conclusion

Optical rectification in metallic tunnel junctions produces dc photocurrent assuming that illumination acts as an ac voltage at optical frequencies across the nonlinear tunneling conduction. The photon-assisted transport theory in tunnel junctions states that the dc photocurrent is a well known function of the I(V) characteristics on a voltage range of the photon voltage \( h\nu / e \). This theoretical prediction is based on the creation of a non-thermal hot carrier distribution function in the metals under optical illumination. We have shown experimentally that this is incorrect in a planar tunnel junction. By comparing the photocurrent generated in a planar junction in the Kretschmann configuration and the measured I(V) characteristics, we have demonstrated that the photocurrent can be described by heating and thermal distribution functions instead. While we have only considered a planar tunnel junction without nanoantenna, the question of the generation of hot electrons in metallic nanostructures for optical rectification or optical detection still raises theoretical questions. As pointed out by Iñarrea et al. in the case of THz detectors in double barrier systems, it is crucial to calculate the transmission coefficient by considering the coupling term \( A \cdot p \) where \( A \) is the vector potential of the electromagnetic field and \( p \) the electronic momentum operator. Note that the coupling between electrons and the electromagnetic field no longer takes place in a single region of the structure but interacts with the barrier. In conclusion, the planar tunnel junction is not a good candidate to highlight the hot carrier distribution in illuminated metallic thin films. The metallic density of states is indeed smooth and it does not allow the realization of the necessary energy filter as it is in a molecular junction.

### Methods

**Non-equilibrium distribution function.** The interplay between photons and electrons in the metallic contact may lead to "hot" electron distribution function or heating. For a moderate increase of temperature, the heating affects a large number of quasiparticles around the Fermi sea whereas the photon-assisted processes brings a small amount of quasiparticles at high energy corresponding to the photon energy \( h\nu \) (see Fig. 6). The excitation of the conduction electrons is done by the absorption of photons of energy \( h\nu \). Assuming that the processes of excitation involve only intraband transitions, electrons of energy \( e \) reach energy \( e + h\nu \). The change in occupancy number \( \delta f_{\text{exc}} \) is given by the difference between the number \( \delta n_{\nu}(e) \) of electrons that access the energy \( e \) and the number \( \delta n_{\nu}(e) \) of electrons that leave the energy \( e + h\nu \) (see Supplementary Note 3).

![Fig. 6 Non-equilibrium distribution functions due to photon-assisted processes or heating.](https://doi.org/10.1038/s42005-023-01149-5)
The lower electrode characterized by a power coefficient $\kappa_{\downarrow} = 1.42 \times 10^{-8}$ (orange line) and the lower electrode characterized by a power coefficient $\kappa_{\uparrow} = 0.69 \times 10^{-8}$ (purple line).

that leave it:

$$dn_<(\epsilon) = A \rho(\epsilon - hu) f_0(\epsilon - hu) \sqrt{\epsilon} (1 - f_0(\epsilon)),$$

$$dn_>(\epsilon) = A \rho(\epsilon + hu) f_0(\epsilon + hu) (1 - f_0(\epsilon)).$$

where $\rho(\epsilon) \propto 1/\sqrt{\epsilon}$ is the density of states of the free electron gas, $A$ is a constant proportional to the energy transferred to the electron gas, and $f_0$ is the equilibrium Fermi-Dirac distribution. The change in the occupancy number is given by $\delta n_{\text{exc}} = \left(dN_<(\epsilon) - dN_>(\epsilon)\right)/\rho(\epsilon)$. The excitation term in Eq. (8) is then directly deducted.

The normalized difference between the energy contained in the non-equilibrium distribution function characterized by absorbed power coefficient $A$ and the equilibrium function at temperature $T_0 + \delta T$ is given by

$$\kappa(A, \delta T) = \frac{\int e \rho(\epsilon) \left[ f_0(\epsilon, T_0) - f_0(\epsilon, T_0 + \delta T) + \delta f_{\text{exc}} \right] \, d\epsilon}{\int e \rho(\epsilon) \left[ f_0(\epsilon, T_0) \right] \, d\epsilon}.$$

The equivalent temperature of excitation $T_{\text{exc}}$ corresponds to $\kappa(A_{\text{exc}}, \delta T_{\text{exc}}) = 0$. Figure 7 gives the values of $\delta T_{\text{exc}}$ for the upper electrode ($A_{\text{up}} = 1.42 \times 10^{-9}$) and the lower one ($A_{\text{dn}} = 0.69 \times 10^{-8}$).

**Data availability**

Relevant data are available from the corresponding author on reasonable request.

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Author contributions
J.G., I.E., M.A., and J.B. designed the project and conceived the experiment. J.G and P.F performed the experiment. All the authors contributed to the analysis of the results and the writing of the manuscript.

Competing interests
The authors declare no competing interests.

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