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Superconducting Tunnel Junctions as detectors for Extreme Ultraviolet Astronomy

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ABSTRACT

Results are presented on the development of superconducting tunnel junctions suitable as imaging spectrometers for use at Extreme Ultraviolet (EUV) wavelengths (10 - 100 nm). Progress in improving the spectral resolution of both niobium and tantalum based devices appears such that tunnel limited resolutions ($d\lambda \sim 0.1$ nm at 10 nm) should be achievable. In addition these detectors offer not only a high degree of linearity ($<1\%$) but a significant efficiency together with a capability to handle rather high count rates. Progress in the development of an imaging instrument through the fabrication of close packed arrays is such that it has become clear that such an imaging spectrometer would represent a powerful and logical next step in the development of instrumentation for EUV astronomy.

Keywords : EUV detectors, Superconducting Tunnel Junctions, Spectroscopy, Astronomy.

1. INTRODUCTION

Extreme Ultraviolet Astronomy (EUV) covers the waveband from ~ 10 to 100 nm, the long wavelength limit being given by the natural absorption provided by the interstellar medium at the Lyman edge (91 nm). While this region of the spectrum was one of the last to be explored, its importance to astrophysics has long been recognized. The EUV is the principle region for emission lines from elements in a hot plasma at a temperature of $T \sim 10^5$ to 10^7 K. Unfortunately the interstellar medium provides a huge absorption factor such that large telescope collecting areas coupled to efficient detectors are required to fully exploit its potential. For example the $1/e$ depth at 10 and 50 nm for an interstellar medium average hydrogen density of 0.1 cm^{-3} is only 100 and 2 parsecs respectively such that in general only relatively nearby stars are observable. Such stars can be detected in a number of limited broad filter bands providing only crude spectral data while only in the case of the very brightest can serious plasma diagnostics be performed through the introduction of a spectrograph to resolve the host of emission lines. Despite these drawbacks the NASA Extreme Ultraviolet Explorer (EUVE) satellite has demonstrated the clear potential of this field to astrophysics. For broad band detection a microchannel plate detector having a KBr coated photocathode at the focus of an EUV telescope was used. Three bandpasses were defined by a series of filters from 7-19 nm, 14-38 nm and 28-76 nm. For brighter objects, follow up spectroscopic observations were performed using gratings to disperse the light onto the microchannel plate. While the moderate spectrograph resolution ($\lambda/\Delta\lambda \sim 200$) was quite sufficient to provide a serious diagnostic tool the typical area of such a system ($\sim 1 \text{ cm}^2$) represents a serious sensitivity limitation. Further details on the payload of the EUVE mission can be found in Welsh et al., and references therein ⁽¹⁾.

In this paper we investigate the possibility to use arrays of superconducting tunnel junctions (STJ's) to take an important step forward in EUV detector technology. With such devices efficient non dispersive imaging spectrometers can be developed which exceed significantly the capabilities of current EUV spectrographs.

2. BASIC DETECTOR CHARACTERISTICS

2.1 General principles

Detectors based on superconducting materials offer some important advantages over those based on semiconductors since the energy gap Δ between the ground state, as represented by the bound Cooper pairs, and the first excited state, containing the broken Cooper pairs known as "quasiparticles", is generally over 10^3 times smaller than the energy gap between the

valence and conduction bands of a semiconductor⁽²⁾. In addition the Debye energy Ω_D is much larger than the superconducting energy gap Δ . This effectively ensures that phonons which are created as a result of the photoabsorption process do not simply contribute to an energy loss process but can break Cooper pairs and create free charge⁽³⁾. Thus for example in bulk tantalum $\Delta_{Ta} \sim 664 \mu\text{eV}$ while Ω_D is as large as $\sim 21 \text{ meV}$.

A superconductor cannot however retain an electric field and therefore less conventional techniques to those used for gas or semiconductors detectors are required to detect the presence of the free charge. One way of detecting the excess quasiparticles produced as a result of the photoabsorption process is by ensuring that they tunnel from one thin superconducting film (S1) in which they are created into another (S2) through a thin insulator (I). To maximize the tunnel probability P_{Tun} the insulating barrier must be very thin, of order 1 nm (i.e. only a few atomic layers). Note P_{Tun} is an exponential function of the barrier thickness. This SIS structure is known as a superconducting tunnel junction (STJ) or Josephson junction and is shown schematically in figure 1(a)^(4,5). A small magnetic field is applied parallel to the junction barrier so as to suppress the Josephson current which results from the tunneling of Cooper pairs at zero bias voltage. Applying a bias voltage $V_b < 2\Delta/e$ ensures that the only allowed tunnel processes involve the transfer of quasiparticles from one film to the other. The flow of quasiparticles in a time t will produce a measurable excess electric current which can be sensed above any background current fluctuations by a charge sensitive amplifier. The amplitude of the current pulse should be directly proportional to the incident photon's energy, while the risetime of the pulse provides a method of event validation. A microscope image of a typical $20 \times 20 \mu\text{m}$ square niobium based STJ deposited on a sapphire substrate is shown in figure 1(b). In this case the two superconducting films are both 100 nm thick niobium films with the base film grown epitaxially on the substrate. The electrical leads are $\sim 1 \mu\text{m}$ wide. Leads can be fabricated from a higher bandgap material to stop quasiparticle losses out of the tunnel region into the leads. Thus for niobium and tantalum based devices the leads are either niobium nitride or niobium respectively.

2.2 The detectors wavelength range

The superconducting tunnel junction has been extensively investigated as a photon detector in the X-ray region of the spectrum where the number of quasiparticles generated after photoabsorption are rather large ($\sim 10^6/\text{keV}$). Early work involved the use of tin as the superconducting film⁽⁶⁾, while later efforts have concentrated on niobium and aluminium^(7,8). Recently niobium & tantalum based devices have also been evaluated as photon counting detectors at near infra-red, optical and ultraviolet wavelengths⁽⁹⁻¹³⁾.

At X-ray and EUV wavelengths the detector must be illuminated from the front (front illumination) rather than as in the UV and optical case where illumination is through the substrate directly onto the high quality epitaxial base film. Front illumination at EUV wavelengths should still however provide rather high efficiencies. Figure 2(a) shows the mean penetration depth l_p of EUV photons in three superconductors currently under development as the basis for STJ's. Only in the case of niobium films for photon wavelengths $\lambda < 15 \text{ nm}$ does l_p exceed the typical top film thickness of $\sim 100 \text{ nm}$. At the longer wavelengths the efficiency will be reduced somewhat by reflection from the surface of the polycrystalline top film. Figure 2(b) illustrates that for Nb and Ta films this reflection however never exceeds $\sim 30 \%$ across the whole band and is insignificant at $\lambda < 200 \text{ nm}$.

The absorption of a photon of wavelength $\lambda(\text{nm})$ in a superconductor is followed by a series of fast processes in which the photon energy is converted into a population of free charge carriers in excess of any thermal population. For typical transition metal superconductors this conversion process is of order of a few nanoseconds. At sufficiently low temperatures (typically about an order of magnitude lower than the superconductor's critical temperature T_c) the number density of thermal carriers is very small and the number of excess carriers N_o , created as a result of the absorption of a photon of wavelength λ , is inversely proportional to the photon wavelength. In general N_o can be written :

$$N_o(\lambda) \sim 7.10^5/\lambda\Delta(T) \quad (1)$$

Here λ is in nm and Δ is in meV. Thus in a Tantalum superconductor at a temperature well below the critical temperature, $T_c \sim 4.5 \text{ K}$ and $\Delta_{Ta} \sim 0.664 \text{ meV}$, the number of free charge carriers $N_o(\lambda)$ created by the photoabsorption of an EUV photon with $\lambda \sim 50 \text{ nm}$ is $\sim 2 \cdot 10^4$. At both optical and UV wavelengths the linearity of the detectors made in either niobium or tantalum is rather high^(11,13).

Figure1(a) : A schematic of a tantalum tunnel junction used in the experiments together with it's orientation in the magnetic field. The device can be operated in a back or front illuminated mode depending on the wavelength.

Figure 1(b) : An scanning electron microscope picture of a typical STJ deposited on a sapphire substrate.

Figure 2 : (a) The mean penetration depth ($1/e$) for EUV photons absorbed in thin films of Nb,Ta & Hf
 (b) The reflectivity at EUV wavelengths from the surface of single crystal films.

2.3 The detectors time resolution

For the case where $V_b < 2\Delta/e$ two tunnel processes exist⁽¹⁴⁾. In the first process an electron tunnels from film 1 to film 2 (the order depends simply on the polarity of V_b) and effectively a quasiparticle is exchanged, while in the second process an electron tunnels again from film 1 to 2 while a quasiparticle is exchanged between film 2 & 1. The combination in series of these two processes lead to an effect known as multiple tunneling which can essentially be viewed as equivalent to an amplification of the initial charge $Q_o^i = eN_o^i(\lambda)$ created in the superconducting film i . If each quasiparticle originally created in the film is transferred across the barrier on average $\langle n \rangle$ times then the average total electrical charge detected would be $\langle n \rangle Q_o^i$. Of course this is a time dependent process since recombination, diffusion losses and quasiparticle trapping will all reduce $Q_o^i(t)$ ^(15,16). The rate of tunneling Γ_{tun} can be written⁽¹⁷⁾ as :

$$\Gamma_{tun,i}^{-1} = 4e^2 N(o) \rho d [(\Delta + eV_b)^2 - \Delta^2]^{1/2} / (\Delta + eV_b) \quad (2)$$

where $N(o)$ is the single spin electronic density of states at the Fermi energy, e the electron charge, ρ is the normal state barrier resistivity, d the thickness of the superconducting film and V_b is the bias voltage applied across the two films. Loss processes will lead to an effective loss rate Γ_{loss} such that $\langle n \rangle \sim \Gamma_{tun} / \Gamma_{loss}$. The intrinsic time resolution Γ_{det}^{-1} of the device is very fast, and can be approximated by $\Gamma_{det} \sim \Gamma_{loss} \sim \Gamma_{tun} / \langle n \rangle$. Typically for a 20 -50 μm sized tantalum based device Γ_{det}^{-1} ranges from ~ 1 -50 μs . In practice the time resolution will be limited by the speed of the signal processing electronics rather than the intrinsic speed of the physical processes occurring in the detector.

2.4 The detectors spectral resolution

The fluctuations in the initial number of quasiparticles N_o depends on the Fano factor F of the superconductor and is the fundamental limit to the spectral resolution⁽¹⁸⁾. The charge amplification produced by $\langle n \rangle$ will degrade however this Fano limited resolution by adding the variance on this tunnel process⁽¹⁹⁾.

The initial fluctuation in the number of charge carriers created in the photoabsorption process combined with the tunnel noise leads to an overall limiting resolution for a perfectly symmetrical junction of the form :

$$d\lambda_T (nm) \sim 2.8 \cdot 10^{-3} \lambda^{3/2} \Delta^{1/2} [F+1+(1/\langle n \rangle)]^{1/2} \quad (3)$$

Here the Fano factor F can be assumed to be ~ 0.22 , considered typical of many of the transition metal elemental superconductors such as tantalum⁽⁷⁾. Thus for tantalum based STJ's the tunnel limiting resolution for the case when $\langle n \rangle \rightarrow \infty$ is ~ 0.2 nm for $\lambda \sim 20$ nm. Figure 3 illustrates this function for the three key superconductors under development in our group. To aid the astrophysical interpretation a range of constant resolving powers (R) are also indicated. Note these tunnel limited resolutions have already been achieved at UV and optical wavelengths⁽¹¹⁻¹³⁾. Clearly at EUV wavelengths a resolving power of $R > 100$ can be achieved in tantalum based devices for $\lambda < 15$ nm. Such devices already exist and results at effective EUV wavelengths are presented in section 3⁽¹²⁾. Of course devices based on hafnium would allow $R > 200$ across the complete EUV band. Such devices, which are in an early stage of development, would however require operating temperatures below ~ 30 mK.

At least two other components contribute to the measured resolution ($d\lambda_M$). These are due to the readout noise of the analogue electronics ($d\lambda_E$) and spatial non-uniformities in the response of the STJ ($d\lambda_S$) and can be added in quadrature to ($d\lambda_T$). The electronics component can be determined from the measured full width at half maximum (dQ_E) of an average test charge $\langle Q_E \rangle$ injected into the preamplifier with the STJ in circuit, such that $d\lambda_E = \lambda(dQ_E / \langle Q_E \rangle)$. The spatial contribution is best determined by illumination at X-ray wavelengths (~ 0.2 nm) where it can be the dominant contributor to the overall resolution.

2.5 The detectors spatial resolution

A number of approaches have been considered at both X-ray and optical wavelengths to provide an imaging capability⁽²⁰⁻²⁴⁾. The simplest and proven approach is to fabricate a close-packed array⁽²¹⁾. Section 3 will provide results from a 3x3 array

currently undergoing tests at X-ray and UV wavelengths ⁽²⁵⁾. The test array consists of 40x40 μm square niobium based devices with a separation of 4 μm between devices leading to a packing fraction of 0.88. This fraction should be possible to increase to 0.95 by reducing the photolithographic requirements to below 2 μm . Device sizes from 100 to 10 μm are quite realistic although the smaller devices will have a lower packing density (~ 0.78). Of course this approach does have the drawback that every device must have its own preamplifier. In addition the top contact to each device will also act as a “dead region” at EUV wavelengths in the required front illumination mode. The larger the format of the array the larger such regions will become.

While such a square array would be suitable for imaging particularly if the number of pixels is increased, a long strip of close packed STJ's could also be used as the detector for a very high resolution spectrograph where order separation is required.

3. EXPERIMENTAL RESULTS

3.1 Experimental configuration

The results described here come from three types of devices of which their key characteristics are summarized in Table I. In all cases the electrical signals from the STJ were read out using a charge sensitive amplifier operated at room temperature about 1 m from the device. Each detected EUV or UV/Optical photon gives rise to a pulse at the output of the preamplifier. The amplitude of this pulse is measured together with the pulse rise time, and corresponds to the total number of tunnelled electrons (charge output) and signal decay time respectively. The electronic noise is continuously monitored through the response to an electronic pulse fed directly into the pre-amplifier. Further details of the experimental configuration can be found in references 10,16,26.

Prior to establishing the spectroscopic performance of a device the key electrical characteristics were derived through the analysis of the I-V function at the specific measurement temperature indicated in Table I. Such characteristics as the band-gap of the device at the barrier together with its resistivity can be determined through such a study.

Table I : The Principle Characteristics Of STJ's Under Test

Parameters	Niobium device	Niobium 3x3 Array	Tantalum Device
Device layup	Nb/Al/AlOx/Al/Nb	Nb/Al/AlOx/Al/Nb	Ta/Al/AlOx/Al/Nb/Ta
Film Thicknesses (nm)	100/120/1/120/100	100/5/1/5/250	100/5/1/5/4/100
Device size (μm)	20x20	40x40 (array 3x3)	30x30
Lead width (μm)	3	Top ~ 1 Bottom ~ 2	2
Lead Material	Nb	Nb	Nb
BandGap	0.44	1.12	0.6
Resistivity ($\Omega\text{-cm}^2$)	$2.2 \cdot 10^{-6}$	$\sim 2 \cdot 10^{-6}$	$2.3 \cdot 10^{-6}$
Pulse Decay Time (μs)	5.0	0.75	12
I_L ($\text{pA}/\mu\text{m}^2$)	<0.1 @ 0.1 mV @ 0.3K	80 @ 0.5 mV @ 1.25 K	0.03 @ 0.1 mV
Measurement Temp (K)	0.3	1.25	0.3
Base Film RRR	$\sim 40\text{-}80$	~ 46	32

3.2 A Niobium/Aluminium based device

The measurements were performed at the electron storage ring, Bessy in Berlin. The SX700 plane grating monochromator of the radiometry lab of the Physikalische-Technische-Bundesanstalt was used ⁽²⁷⁾. Details of the overall experimental configuration can be found in Lumb et al. 1995⁽²⁶⁾. The important detail is that the STJ was illuminated by the external synchrotron source from 10 to 25 nm while at an operational temperature of 0.3 K.

Figure 3 : The tunnel limited resolution at EUV wavelengths for symmetrical STJ's fabricated from thin films of Nb, Ta or Hf.

Figure 4 : The charge spectrum from a Nb-Al based STJ when illuminated by EUV photons at a wavelength of 10 nm.

Figure 4 illustrates a typical spectrum obtained from a 20 μm device at 10 nm (~ 120 eV). The corrected resolution $d\lambda_C$ is above the tunnel limited resolution. From the higher energy X-ray data the spatial contribution $d\lambda_s$ to the resolution is $\sim 1-2$ % in this device and as such would contribute somewhat to the corrected resolution $d\lambda_C$ at EUV wavelengths. Another source of degradation in the spectral resolution is due to the rather large infrared flux which introduces an additional variance on the signal. This is discussed in more detail in section 4.

3.3 A Tantalum based device

The spectroscopic measurements on Ta based devices have been performed in a ^3He cryostat at a base temperature of ~ 0.3 K^(12,13). As shown in figure 1, the device was illuminated through the sapphire substrate (back illuminated), via a fibre optic. All optical illumination described here was in this back-illuminated mode. An LED was used as a pulsed light source with wavelength of 820 nm and pulse duration time of ~ 100 ns much faster than the estimated tunnel time from the device $(\Gamma_{\text{tun},1})^{-1}$. This configuration is due to current limitations in illuminating the device with genuine EUV photons at 0.3 K. Since the device is sensitive to single optical photons from the LED, pulses containing a fixed number of such photons arriving on the detector within such a short time can simulate an EUV photon. If the number of photons falling onto the STJ in a pulse is p we can define an effective wavelength $\lambda_{\text{EUV}} = 820/p$. Care must be taken with this approach however since the 820 nm photons are distributed uniformly over the detector thereby modifying somewhat the contribution to the measured resolution $d\lambda_M$ from the spatial contribution $d\lambda_s$. In addition the initial energy density in the detector is also lower than for a single EUV photon event. Knowledge of $d\lambda_s$ from X-ray data together with the rather low energies involved at EUV wavelengths mean that these points are not considered as major issues.

With such an LED illumination approach it is expected that the average number of photons $\langle p \rangle$ absorbed in the base film during the pulse will vary depending on the pulse duration and the power applied to the LED. In addition the distribution of the number of pulses containing p photons will be according to a Poisson distribution. If $\langle Q(\lambda) \rangle$ is the average detected charge for a single photon then the amount of charge detected from a pulse containing p photons is simply $p\langle Q(\lambda) \rangle$. Figure 5(a) shows a typical spectrum obtained from the device when illuminated by the LED. This data can be fitted to a simple model which assumed that the observed charge is distributed about the mean charge $\langle pQ(\lambda) \rangle$ as a gaussian with a standard deviation $\sigma Q \geq \sigma Q_E$. The system noise (junction plus electronics) was determined using a pulsed stimulation of the pre-amplifier at about the same average charge output as the LED optical spectrum. For each peak both the intensity, $\langle pQ(\lambda) \rangle$ and σQ were free parameters in a multiple gaussian fit model. Note the distribution of photons from the LED is not monochromatic with $d\lambda_{\text{LED}} \sim 40$ nm at a mean wavelength of 820 nm which can drift somewhat with temperature.

It is clear from Figure 5(a) that single 820 nm photons have been detected above the noise and that the intensity distribution of pulses follow the expected Poissonian statistics. The values of p for each peak is also indicated above the individual peaks. The inset illustrates the linearity of the detector by showing the mean charge $\langle pQ \rangle$ and its associated error $d\langle pQ \rangle$ versus number of photons p per pulse together with the effective wavelength λ_{EUV} . The best straight line fit to this data is also indicated. The response is effectively equivalent to illuminating the detector with photons of wavelength ranging from 820 to ~ 58 nm, i.e. from the optical to the extreme ultra-violet. The linearity is extremely high as would be expected from photons which produce such a low number density of quasiparticles. To extend this approach towards even shorter EUV wavelengths the LED intensity was increased. Figure 5(b) shows the resultant pulse spectrum for $p \sim 20$ to $p \sim 45$. This is equivalent to λ_{EUV} ranging from 41 to 18 nm. The resultant linearity of the mean charge output is also shown in the inset. Overall the linearity of the detectors charge output with p is well below 1%. The intrinsic resolution of the detector $d\lambda_C$ after removal of the noise from the electronics together with the known distribution in the spectral response of the LED ($d\lambda_{\text{LED}} \sim 40$ nm) can be written as $d\lambda_C^2 \sim d\lambda_M^2 - d\lambda_E^2 - d\lambda_{\text{LED}}^2$. This resolution is shown in figure 6 as a function of the effective wavelength λ_{EUV} together with the tunnel limited resolution for tantalum $d\lambda_T$. These are rather close with the difference due possibly to drifts in the LED response which was not temperature stabilised.

Figure 5 : The spectra obtained by irradiating a tantalum device with pulses of 820 nm radiation from an LED. Here the intensity of the LED was changed between (a) and (b) so as to change the photons per pulse.

Figure 6 : The corrected resolution $d\lambda_{\text{C}}$ as a function of effective EUV wavelength λ_{EUV} . The best straight line fit through the data is also indicated together with the tunnel limited resolution $d\lambda_{\text{T}}$.

3.4 A Niobium based array

As an initial step towards a practical imaging capability a limited 3x3 array based on niobium has been fabricated⁽²⁵⁾ and is shown in figure 7(a). These test arrays while designed for soft X-ray applications can also be used to assess the longer wavelength capability. The array, was illuminated at UV wavelengths (225 nm) at a temperature of 0.3 K in a He³ cryostat in the back illumination mode. These types of arrays have demonstrated a key issue that the Josephson current for all devices can be suppressed relatively uniformly for the same applied magnetic field. The mean charge output for each "pixel" is shown in figure 7(b). Again with these devices the spatial variation contribution to the resolution $d\lambda_s$, as determined from X-ray measurements above $\lambda > 1$ nm, was $\sim 2\%$. The inset illustrates the typical spectrum at 225 nm from one device in the array. The measured resolutions $d\lambda_M$ was typically ~ 90 nm, far larger than expected from the spatial and tunnel contributions.

4. THE INFRARED FLUX

Any application of a superconducting tunnel junction for EUV astronomy must also consider the effect of infrared background radiation. For wavelengths greater than a few microns the infrared flux from room temperature components could be considerable. These photons can still break Cooper pairs effectively increasing the thermal current in the device. This is equivalent to raising the operating temperature of the device. In detecting and measuring the energy of an EUV photon it is however not the underlying DC current which presents the problem but rather its statistical variation which adds noise to the signal pulse thereby degrading the energy resolution of the device⁽²⁸⁾. This flux must therefore be reduced for any practical application initially through careful optical design. The superconducting top film of the STJ acts to some extent as a reflector of the IR flux. At 10 μm Tantalum reflects $\sim 98\%$ of the photon flux.

Clearly the IR fluxes are such that thin film blocking filters would be required which undoubtedly will reduce the wavelength response in the EUV as well as the overall system sensitivity. Such cryogenic filters are under development - see for example the work on the cryogenic filters for the X-ray Bolometer XRS for Astro-E⁽²⁹⁾. At longer wavelengths considerable progress in the last few years has been made⁽³⁰⁻³²⁾.

Note that the optical and UV flux is not such a problem (depending on rate) since the STJ photon counts and can handle rates of 10 kHz, limited primarily by the signal processing electronics response time. Such photons would be vetoed by the lower level discriminator due to their lower energy.

5. CONCLUSION

In conclusion we have shown that tunnel limited resolutions could be achievable at EUV wavelengths using STJ's. Close packed arrays are now being fabricated which should allow an imaging capability. These high efficiency devices should provide a major tool for the study of EUV emission from hot astrophysical plasmas. Figure 8(a) shows, for a Ta based STJ, the tunnel limited response to such a plasma at a temperature of 10^5 K with an interstellar absorption of 10^{19} H-atoms cm^{-2} , equivalent to a distance of ~ 300 pc for a mean density of 0.1 H-atoms cm^{-3} . The equivalent response from an STJ based on hafnium is also shown in figure 8(b). A wealth of emission features can be observed. The insets simply highlight the region around 20 to 40 nm where a significant number of features appear in the spectrum.

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Figure 7(a) A microscope image of a 3x3 test array of 40 μm square devices with a common ground lead. Leads are either 1 or 2 microns wide while the separation between base electrodes is $\sim 2 \mu\text{m}$. Each device can be biased at the same voltage and all have their Josephson currents suppressed by the same magnetic field.

Figure 7(b) : The signal variation from device to device in the 3x3 array when illuminated by 225 nm UV photons. The inset shows a typical spectrum from one device in the array.

Figure 8 : The response of a Ta (a) & Hf (b) based STJ to the EUV radiation from a hot plasma at a temperature of 10^5 K and an interstellar hydrogen column density of 10^{19} H-atoms cm^{-2} .

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