

## Superconducting Confined Electron Devices for Possible Application as Submillimeter Wave Detectors

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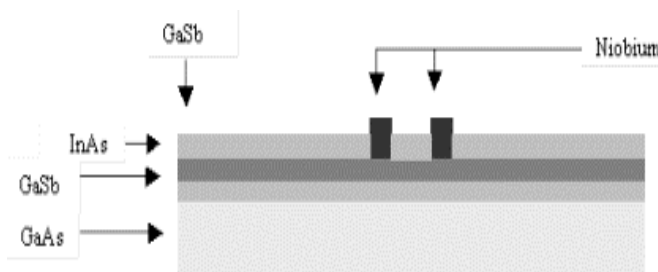
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Electrons can be confined by sandwiching semiconductors between superconducting deposits. Such structures exhibit quantized energy levels and resonant conductance states that can be depopulated by exposure to electromagnetic radiation of the correct wavelength. This results in large changes in the conductance of these devices which can form the basis of radiation sensing. What's more, the energy levels are tunable by varying the temperature and/or an external magnetic field. When integrated with antennas or horn feeds, such superconducting quantum wells could well be used as detectors for Tera hertz radiation for both photometric and spectroscopic applications.

At a normal-superconductor interface electrons undergo a charge conversion process called Andreev reflection that transforms single electrons in the normal phase into Cooper pairs in the superconducting phase<sup>1</sup>. In essence, lone electrons pair up with momentum ( $\otimes$  k vector) and spin opposed electrons from the Fermi sea to form Cooper pairs which travel inside the superconductor. Because Andreev Reflection effectively doubles the unit of charge carried across the interface so it appears as a reduction in the resistance of normal-superconducting junctions. The probability of this process is energy dependent – lower energy electrons have a higher probability of Andreev reflection than higher energy electrons. Consequently, on a measurement of junction differential resistance versus a negative to positive bias current swing, Andreev reflection appears as a dip centered at zero bias. The smooth dependence of Andreev reflection probability on energy is modified when there are two interfaces in a system as for example when a normal material is sandwiched between two superconducting barriers. This arrangement forms a quantum well where certain electron energies have reduced Andreev reflection probability. At these energies, electrons reflect repeatedly between the superconducting barriers and cross transport is inhibited. These so called Andreev bound states result in resonant enhancement of differential resistance, which appear as small peaks superimposed on the Andreev reflection background<sup>2</sup>.

A normal-superconducting-normal structure called a superconducting quantum well (SQW) is best formed by depositing superconducting stripes on a high mobility small bandgap semiconductor, like InAs. This results in a lateral, instead of the more conventional, vertical junction structure. We fabricated a structure like this using techniques described elsewhere<sup>3</sup>. Niobium was used as the superconductor and a GaSb/InAs/GaSb quantum well was used as the semiconductor. The two niobium stripes were typically 1  $\mu$ m apart and contained between two voltage probes. These were deposited directly on the InAs well region by etching away the top GaSb layer locally. The resulting structure is shown in [figure 1](#).



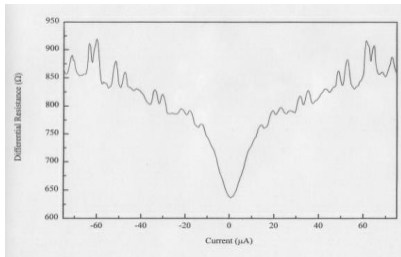
[Figure 1](#)

When cooled to temperatures below the critical temperature of the niobium thin film stripes, the region of InAs underneath becomes superconducting owing to proximity effect. The two-dimensional electron gas is thus further confined between the two proximity induced superconducting barriers. Andreev bound states are formed in such a superconducting quantum well. The levels are found in pairs:  $E_n^+ / E_n^-$ , which coalesce if there is no phase difference between the left and the right superconducting banks. In that case the separation between the energy levels is given by<sup>4</sup>:

$$dE = E_{n+1}^+ - E_n^+ = E_{n+1}^- - E_n^- \sim h p v_F / d$$

Here,  $v_F$  is the Fermi velocity of electrons in the well and  $d$  is the width of the well.

These so-called Andreev bound states (ABS) can be regarded as standing waves formed by the reflection of electrons between the two superconducting barriers. If the differential resistance of the system is measured as a function of current flowing through the Hall bar, a large dip in resistance, at low bias, is observed due to Andreev reflection with Andreev bound state structure seen at higher energies. This is seen in [figure 2](#).



**Figure 2**

With rise in temperature or the application of a magnetic field (in the range of 10 mT to 200 mT) the lateral penetration of order parameter inside the well region is reduced. A magnetic field leads to a similar effect. This effective widening of the SQW, according to the equation above, leads to a reduction of ABS energies. Measurements have shown that this is indeed the case: ABS features do move down to lower energies when either the temperature or an applied magnetic field is increased<sup>5</sup>. The S-N-S system, therefore, provides a means of tuning its spectrum of energy levels. Electrons can be removed from bound states by the application of energy sufficient to cause interlevel transitions. This should suppress the current blocking action of the ABS and result in conductance enhancement *at energies that correspond to ABS levels*. In principle, it should be possible to ‘tune’ the device by properly biasing it at the location of a convenient ABS level. Then only radiation capable of depopulating the chosen energy level would induce transitions and thus be detected. Hence, the proposed arrangement can be utilized as a detector of electromagnetic radiation with the unique feature that in spite of the detection being incoherent, the detector is tunable over a range of wavelengths. For our quantum well system with electron sheet density of  $\sim 2 \times 10^{16} \text{ m}^{-2}$  the Fermi velocity comes out to be  $1.6 \times 10^6 \text{ m/s}$ , then for a 1 mm wide well, equation 1 predicts an ABS energy spacing that corresponds to 21 meV i.e. the energy of 5 THz photons. If the well width is reduced to 0.1 mm, this increases to 50 THz. This region of the electromagnetic spectrum has so far only been accessible to bolometric detection technologies that don’t have any frequency selectivity. Thus SQW detectors can provide a long sought after means of carrying out observations in this region. We have found that moderately strong (estimated to be a few microwatts) broadband radio frequency (RF) radiation, can overwhelm the system and destroy the transitions<sup>6</sup>.

The metallic niobium deposits can be designed as integrated antennas that receive RF power from a suitable dielectric lens or feed horn and transfer it to the InAs well region. A suggested implementation is shown in [figure 2](#). Another advantage of this design is that the detector can respond to radiation having wavelength larger than the size of the SQW itself. It shouldn’t be too difficult to extend this scheme to two-dimensional arrays with rows of detector pixels formed on common Hall bars.

Summarizing, we suggest using superconducting quantum wells as a novel form of astronomical radiation detector. The outstanding advantages of this device are: easy tunability, efficient radiation coupling and the ease of fabricating large format two-dimensional imaging arrays.

## References:

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