challenging than TESs and work towards sensor arrays is still at a very early level of development.

Athermal sensors measure excitations, typically superconducting quasiparticles, created by an incident particle or photon. Examples include superconducting tunnel junctions (STJs) and microwave kinetic inductance detectors (MKIDs). To date, the resolution of STJs and MKIDs is inferior to TESs [17–19] and the absence of a multiplexing scheme for STJs is an obstacle to their use in large arrays. In contrast, high multiplexing factors are possible with MKIDs. In recent work, MKIDs have been used as thermal sensors for the temperature of an isolated platform in much the same way as TESs [20].

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2.2. Absorbing structures

TES detectors typically rely on photoelectric absorption of x-rays and gamma-rays. The absorbed photon is annihilated and its energy E_g is transferred to a single electron that acquires kinetic energy $E_g - E_\mathrm{b}$ where E_b is its previous binding energy. The hot photoelectron then relaxes to the Fermi level by electron-electron and electron-phonon scattering. The energy lost in a single electron-phonon event is limited to $k_\mathrm{b} T_\mathrm{D}$ where T_D is the Debye temperature or 10’s of meV so electron-electron scattering is initially a more efficient cooling mechanism. As electronic excitations approach the Fermi level, cooling by electron-phonon scattering becomes more important. Hot phonons either excite additional electrons or escape to the heat bath. The escape of hot phonons corresponds to lost signal and event-to-event fluctuations in this loss are a source of noise [21, 22].

Superconducting detectors are often designed to reduce these losses either by locating the absorber on a micromachined membrane or by isolating the absorber above the substrate on small-area supports as shown in figure 2. The initial relaxation cascade is completed within about 10^{-10} seconds depending on the material, and results in a partitioning of the energy of the absorbed photon among the electron and phonon systems of the absorber. In a normal metal, electronic energy takes the form of an increased electron temperature; in a superconductor, electronic energy takes the form of additional quasiparticles. Several authors have treated the rapid relaxation cascade and estimated the subsequent division of energy among electrons and phonons [23–25].

In an ideal absorber, all the energy of the photon is converted to a measurable form resulting in a well-defined photopeak whose width is limited by noise mechanisms after the initial thermalization process. However, numerous non-idealities are possible. Even at very low levels, Compton scattering produces a weak continuum of events below the main photopeak as scattered photons can leave the sensor resulting in partial energy deposition. The likelihood of Compton scattering grows with photon energy for the energies likely to be encountered by TES detectors [26]. The escape of some of the initial hot photoelectrons from an exterior surface of the absorber will also produce a weak low-energy continuum [27, 28]. The amplitude of this continuum is operationally important since it affects the ease of observing weak photopeaks at energies below a stronger spectral feature [29]. The composition of the absorber can also contribute non-idealities. Insulating absorbers work poorly because of the creation of long-lived electronic excitations during the relaxation cascade that are lost to the subsequent energy measurement. Since the energy to create an electron-hole pair is about 10 eV in an insulator, even small event-to-event fluctuations in the number of such pairs will degrade sensor resolution. Similar effects can occur in semiconductors with finite gaps. Normal metals, semimetals, zero-gap semiconductors, and some superconductors have worked well as absorbers because they quickly and reproducibly thermalize close to 100% of deposited energy.

In superconducting detectors for photons below about 1 keV of energy, the sensing structure usually provides enough stopping power to also act as the absorber. For higher energy photons, an absorber is usually needed. For thermal detectors such as TESs, the absorber should combine high stopping power, low heat capacity, and good thermalization properties. Between 1 and 10 keV, the absorber is typically another film in good thermal contact with the sensing element. The semimetal bismuth is widely used because of its high atomic number ($Z = 83$) and very low specific heat. Gold is also commonly used because of its high atomic number ($Z = 79$) and low specific heat for a normal metal. An absorber containing 3 um of gold has a 92% chance of absorbing a 6 keV photon.

At energies above 10 keV, absorption in thin films becomes less likely. Electrodeposition can be used to grow films 10’s or 100’s of microns thick to absorb high energy photons. Alternatively, a bulk foil prepared separately can be attached to a thin-film sensor. This attachment is most easily done with a cryogenic epoxy, but use of an insulating epoxy implies that energy can only leave the foil in the form of phonons. Superconducting absorbers are attractive because the electronic contribution to the specific heat of a superconductor scales as $\mathrm{e}^{-T_\mathrm{c}/T}$. For $T/T_\mathrm{c} \approx 0.1$, this contribution is effectively zero which preserves energy resolution. However, achieving rapid and efficient thermalization of energy deposited in bulk superconductors remains a challenge and the use of bulk superconducting absorbers is an active area of research [25]. In this context, we take thermalization to mean the conversion of photon energy into phonon energy that can leave the absorber and heat the sensor. Simple models of energy thermalization in a bulk superconductor predict that energy will remain in the quasiparticle system for impractical lengths of time because the time for a recombination phonon produced by the annihilation of two quasiparticles to break another Cooper pair is typically much shorter than the time for a recombination phonon to exit bulk material through a glue joint. This effect results in a greatly extended quasiparticle lifetime. However, actual pulse durations from some superconductors (Pb, In, and Sn for example) are far shorter than the calculated thermalization times, posing the question of why these superconductors work as absorbers as well as they do. Thermalization in superconducting tin ($Z = 50$) is particularly fast and complete. Trapped flux, impurities, and other sources of local energy-gap suppression may accelerate quasiparticle recombination and lead to the generation of recombination phonons that cannot break Cooper pairs in the higher gap regions of pristine material, thus facilitating phonon escape. Further, recent work indicates that the intrinsically anisotropic energy gap and density of states in clean, bulk tin powerfully accelerate thermalization [30].

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Bulk absorbers are often attached to a sensing structure by a cryogenic epoxy [31–34]. However, it has recently been shown that at least some epoxies are the source of extended heat release after the absorption of a photon that delays sensor recovery and is easily mistaken for slow thermalization in the absorber. When a metallic joint was used to connect a Sn absorber to a TES thermometer, >95% of deposited energy emerged from the device on prompt timescales indicating that thermalization occurred much faster than the thermal time constants of the device [35].

Certain superconducting materials such as tantalum are, in principle, extremely attractive for x-ray and gamma-ray absorbers. Tantalum has a high atomic number ($Z = 73$) and a high Debye temperature so that its phononic specific heat is very low. However, detectors using bulk tantalum absorbers show time constants of 10^{-2} s or longer that are largely impractical [36]. While these extended time constants may be due to slow thermalization, both historical and contemporary measurements of the heat capacity of Ta are much higher than the expected phononic contribution, an excess which will slow device recovery [37, 38]. In contrast, both historical and contemporary measurements of the heat capacity of Sn are close to the expected values [38, 39].

While rare, other absorbing schemes combine athermal and thermal processes. For example, phonons or quasiparticles created in a large volume absorber can be coupled to a smaller sensor. Some resolution degradation is often associated with such schemes.

2.3. Thermal isolation

If a thermal detector is in near perfect thermal contact with the outside world, then the pulses created by incident x-rays and gamma-rays will be so fast that they exceed the bandwidth of realistic amplifiers. Hence, some thermal isolation is necessary. A thermal impedance to the outside world that significantly exceeds the thermal impedances within a device also helps ensure that the device response is independent of the position where a photon is absorbed.

Thermal isolation can be achieved via electron-phonon decoupling, acoustic mismatch at film interfaces, or by limiting phonon transport. Phonon transport can readily be tailored using geometry and material choice. TES detectors have been isolated on patterned SiN and SOI membranes with thicknesses of about 100 nm to a few microns. Detectors have also been isolated using full-thickness Si wafers patterned into meandering beams. Detectors can be fabricated on bulk substrates using a combination of electron-phonon decoupling and acoustic mismatch for thermal isolation. The power flow due to acoustic mismatch scales as film area and the fourth power of temperature. Power flow due to electron-phonon decoupling scales as film volume and usually as the fifth or sixth power of temperature. So, electron-phonon decoupling will be the limiting thermal impedance at very low temperatures and in very thin films. As mentioned above, the escape of phonons created during the initial relaxation cascade is a risk in devices on bulk substrates that can be avoided by elevating the absorber as shown in figure 2. We conclude by noting that electronic energy is prevented from leaving the TES through the higher gap leads because of the low electronic thermal conductivity of superconductors and because of Andreev reflection at the TES-lead interface.

3. Sensor readout

The choice of readout approach for cryogenic sensors is highly dependent on the type of sensor being measured. In some cases there is a natural choice for the readout. For example, MKIDs are constructed from microwave resonators and so are naturally measured in the frequency domain. TESs are almost always measured using SQUIDs as sensitive ammeters. SQUIDs are compatible with a number of different readout implementations. The independence of the measurement SQUIDs from the TES sensors poses some mechanical complexities but also allows separate optimization of the sensors and readout. Crucially, SQUIDs enable multiplexed readout of TESs meaning the readout of many sensors using a smaller number of amplifier channels. Multiplexing has proven crucial to the development of large arrays of sensors since it reduces the mechanical, thermal, and financial burden of having readout circuitry for each pixel. Some other cryogenic sensors, i.e. silicon thermistors and STJs, lack a readout that is compatible with multiplexing. The most noticeable difference between multiplexing implementations is the choice of the basis that is used to separate the signals from different sensors [8, 42]. The different modulation functions being pursued for TESs are shown in figure 3. Besides the encoding and decoding steps, multiplexing also requires the combination of different sensor signals into a smaller number of channels. This combination necessitates a band-pass limiting filter for each sensor so that their broad-band noise contributions are not summed.

Multiplexing is almost always important in x-ray and gamma-ray applications where large arrays of cryogenic sensors are needed to boost collection efficiency and count rate. For x-ray and gamma-ray applications, much of the progress since the last major review of cryogenics sensors [1] has been enabled by the emergence of array-scale readout systems. In what follows, we provide brief summaries of the different types of SQUID multiplexing, review progress achieved in the last decade, and describe the advantages and disadvantages of each approach. The discussion is organized by multiplexing basis set. Proceeding in order of technical maturity, we will discuss time-division multiplexing (TDM), code-division multiplexing (CDM), and low-frequency frequency-division multiplexing (FDM), followed by promising recent results from microwave resonator based readout.