Snowmass2021 - Letter of Interest

Towards quantum-limited transistor microwave amplifiers

Thematic Areas: (check all that apply ☐/■)

■ (CF2) Dark Matter: Wavelike
■ (CF3) Dark Matter: Cosmic Probes
■ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
■ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
■ (IF7): Electronics/ASICs
■ (IF9): Cross Cutting and Systems Integration

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Abstract:

Diverse astrophysical applications ranging from dark matter searches to wide area millimeter wave surveys require low noise transistor microwave amplifiers, typically based on high electron mobility transistors. Present devices achieve noise figures around 5 times the quantum limit up to 100 GHz; above this frequency low noise IF amplifiers are required to process the output of superconducting mixers. A need exists to develop transistor amplifiers with noise figure closer to the quantum limit and ideally less than 2X quantum in the range of 1-300 GHz. The availability of such instrumentation would have a transformative impact on many fundamental studies including millimeter wave surveys, dark matter searches, and infrared-optical astronomy using MKIDS.

Low noise transistor microwave amplifiers (LNAs) are a key instrumentation technology in diverse areas of fundamental physics. Nearly all radio telescopes around the world employ cryogenic InP high electron mobility transistors (HEMTs) as the first-stage amplifier[1]. Further, LNAs are widely used in other areas of fundamental physics, including for millimeter wave surveys[2], dark matter searches[3], and infrared-optical astronomy using MKIDS[4].

Although superconducting amplifiers such as Traveling Wave Parametric Amplifiers (TWPAs) offer quantum-limited noise performance,[5] and possibly even below the quantum limit using squeezing, they have a number of drawbacks. First, the cryogenic requirements are considerably more complex than for HEMTs owing to the lower operating temperature. Second, despite their favorable noise figure, TWPAs and related amplifiers generally exhibit narrower bandwidth and less gain than HEMTs. Finally, TWPAs are considerably more complicated to fabricate and operate and thus add to the overall complexity of an instrument.

These factors drive a need for transistor amplifiers with lower noise figure. Figure 1 shows the state-of-art noise figure for InP HEMTs versus frequency. From 1-100 GHz, the noise figure is around 5X the quantum limit; above this frequency the noise figure degrades rapidly. This limitation affects many astrophysical studies because often the sensitivity of the overall instrument is set by the first stage amplifier. As an example, a recently introduced scheme using a microwave qubit to search for dark matter is at present limited by amplifier noise[3]. At higher frequencies above 100 GHz, the lack of low noise amplifiers complicates efforts to create, for example, focal plane arrays, which in turn affects the efficiency of wide area surveys.

Can HEMT amplifiers be realized with even lower noise figure approaching the quantum limit? At present, this is an open question. The strategies to answer it can be divided among efforts to improve the noise figure of the dominant HEMT architecture, and those that consider alternate architectures that exhibit better potential for scaled devices that can operate with low noise at frequencies above 100 GHz.

First, consider the workhorse HEMT consisting of an InGaAs channel on an InP wafer. The noise of these devices is generally attributed to (1) thermal noise in the gate metal added at the input and (2) 'drain noise' added at the output. The actual cryogenic noise performance thus depends on whether the gate metal can be adequately heat sunk to the cold stage. Our prior studies suggest that the gate metal is in fact not well thermalized to the cold stage owing to local self-heating in the device, leading to thermal noise considerably in excess of what would be expected for physical temperatures below 20 K.[6] If this self-heating can be mitigated by cryogenic engineering, a factor of 2 decrease in noise figure can be expected[7].

The remainder of the noise is due to 'drain noise,' the origin of which is under debate but is generally believed to be related to intervalley electronic transitions caused by the large peak electric fields on the drain side of the gate. Here, decreases in noise figure could be achieved by modifying the electrostatics of the gate to decrease this peak field while minimizing the impact to other DC and RF microwave properties. Both of these directions are under active investigation in the PI's group.

Second, alternate transistor architectures need to be considered for their potential to exhibit improved noise figure, particularly over 100 GHz. The noise figure of a transistor is inversely proportional to its unity gain cutoff frequency, f_T. Therefore, devices with geometrically scaled down dimensions and hence higher cutoff frequency would be expected to yield improved noise figure. Unfortunately, in their present form, HEMTs are limited in their ability to scale down owing to gate leakage, or the tunneling of electrons from the channel of the transistor through the Schottky barrier to the gate[8]. This leakage decreases the current gain and deteriorates noise performance[1]. Further, scaling the source-drain distance generally exacerbates short-channel effects that again negatively impact noise figure.

Alternate device architectures thus must be considered to realize lower noise amplifiers, especially above

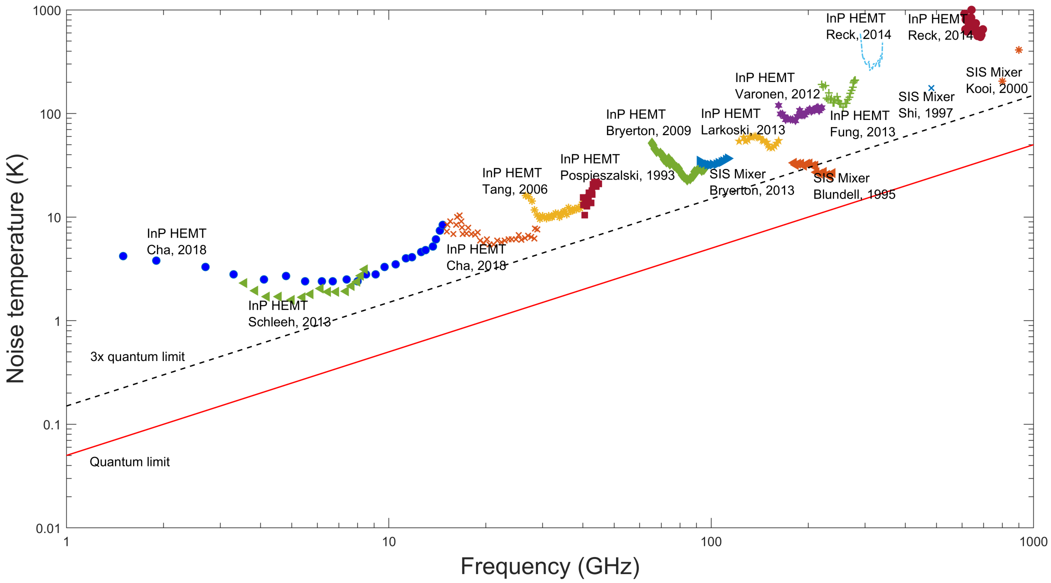

Figure 1: State of the art noise figures for transistor amplifiers. HEMTs are the preferred technology up to 120 GHZ; SIS mixers followed by IF amplifiers exhibit the best noise performance from 120 GHz to 1 THz.

100 GHz. For example, the metal-oxide-semiconductor high electron moblity transistor (MOSHEMT) addresses one of the shortcomings of the traditional HEMT related to gate current leakage.[9] As its name suggest, this transistor employs an electrically insulating oxide layer rather than the conventional semiconductor Schottky barrier used in HEMTs. This oxide barrier limits gate current leakage while increasing gate-channel capacitance, a key characteristic needed to improve the gain of the device. While some fabrication hurdles remain to be overcome for this technology to be competitive with conventional HEMTs, it already shows promise. A MOSHEMT with record f_T of 511 GHz and g_m of 2200 mS/mm has recently been reported[10], values that are comparable to those of state-of-art HEMTs. However, the crogenic noise performance of these and related devices has not been characterized. Focused study and optimization of these devices is required to achieve improved noise figure.

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