Meissner Effect Transistor

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***Abstract*—The operation of conventional transistors is based on modulating the conductivity within a semiconductor by the application of an electric field. Meissner Effect Transistor (MET) has a complimentary device architecture within which the conductivity of a superconducting bridge is modulated by an applied magnetic field by way of the Meissner Effect. The upper cut-off operating frequency is dependent on Cooper pair relaxation time. Here we introduce the theory behind the operation of the MET, as well as initial proof-of-concept laboratory measurements.**

***Index Terms*—Cooper Pair, HEB, Meissner Effect**

I. Theory of Operation

Superconductors are made by forming Cooper pairs between electrons. The electrons in a Cooper pair have opposite (antiparallel) spins. Magnetic fields work to align the electron spins. Meissner and Ochsenfeld (1933) found that if a superconductor is cooled in a magnetic field to below the transition temperature T_c, then at the transition, the lines of induction B are pushed out. Likewise by imposing a magnetic field, B, on a superconductor it is possible to break the Cooper pairs in a controlled way, thereby modulating the conductivity of the superconductor.

The theory of operation for a Meissner Effect Transistor (MET) is analogous to a Field Effect Transistor (FET). A standard FET has 3 ports formed by metallic electrodes deposited on a semiconductor substrate.These ports are the gate (G), source (S), and drain (D). A time varying electric field applied to G modulates the conductivity in the underlying channel exponentially; i.e. small changes in the time varying gate voltage can cause large variations in the channel conductivity. In case of MET, the ``channel'' is a thin superconducting bridge and the gate electrode is replaced by an oscillating magnetic field, H_a that modulates the bridge's conductivity also in a nonlinear manner (Fig. 1). The greatest gain (or sensitivity) occurs when the bridge is magnetically or thermally biased near the point of going normal

A linear small signal model for an MET can be derived using the same approach as is used for an FET[1]. The small signal drain current i_D is a function of both the small signal drain

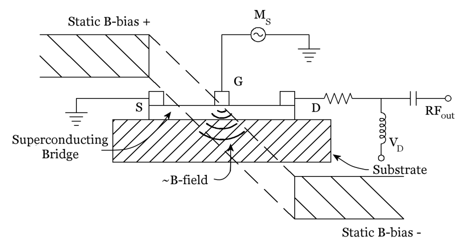

Fig. 1. Operating principle of an MET. A time varying magnetic field applied at the gate electrode (G) modulates the conductivity of the superconducting bridge.

voltage v_{DS} and the magnetic field applied to the bridge H_a.

$$i_D = f\left(H_a, v_{DS}\right) = b_m H_a + \frac{1}{r_d} v_{ds} \tag{1}$$

where

$$b_m = \left.\frac{\partial i_D}{\partial H_a}\right|_{V_{DS}} \approx \left.\frac{\Delta i_D}{\Delta H_a}\right|_{V_{DS}} = \left.\frac{i_d}{H_a}\right|_{V_{DS}} \tag{2}$$

is the magnetic transconductance. The magnetic drain resistance r_d can be defined as

$$r_d = \left.\frac{\partial v_{DS}}{\partial i_D}\right|_{h_a} \approx \left.\frac{\Delta v_{DS}}{\Delta i_D}\right|_{H_a} = \left.\frac{v_{ds}}{i_d}\right|_{H_a} = \frac{1}{\sigma_N}\frac{\delta L}{W\lambda_L^2}\left(\frac{H_a}{H_c}\right)^2. \tag{3}$$

Considering the gate current noise is uncorrelated with the drain current noise, the MET minimum noise temperature is given by[2]

$$T_{\min} = 4\left(\frac{f}{f_T}\right)^2 \frac{r_{gs}}{r_{ds}} T \tag{4}$$

where f is the operating frequency (Hz), f_T is the upper cut-off frequency, $r_{ds} = \frac{1}{\sigma_N}\frac{\delta L}{W\lambda_L^2}\left(\frac{H_a}{H_c}\right)^2$ and $r_{gs} = 2\pi f L_k$.

For MET, the upper cut-off operating frequency is dependent on Cooper pair relaxation time τ_0. In case of Niobium[3],

$$\tau_0 = \frac{\pi\hbar}{8k_B(T - T_{c0})} = 8.33\times10^{-13}\ \text{s} \tag{5}$$

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Fig. 2. Expected minimum MET noise temperature vs range of operating frequency. At !$_\#$ = !"#"#$% , !$_{\%\&}$, = !"#"$.

II. Test Set-Up & Experimental Results

The MET is bolted on to the cold plate inside the helium cryostat. Voltage biasing is provided using a bias tee connected through the pre-amplifier to the SIS & Magnet Bias Box. Backing pump and Turbo pump are used to pull vacuum in the cryostat. The cold head connected to a compressor is then employed to cool the cold plate down to 90 K. Cryostat is then filled with liquid helium. Once the cold plate is cooled down to 4.4 K, the magnet is moved into position and Voltage-Current characteristics of the MET is recorded.

Fig. 3. Left: Prototype MET inside of cryostat. Right: MET Experimental Set-up

A pulse width modulator is used to modulate the current supply to the solenoid at low frequency (around 4-6 Hz). The resulting $$_{!"\#}$ modulates the conductivity of MET. SIS & Magnet Bias box is used to supply #$_{!"}$ and read the voltage equivalent of #$_{!"}$. A lock-in amplifier is used to pick up the voltage equivalent of #$_{!"}$. An Arduino board is programmed to read in this voltage and convert it to #$_{!"}$.

In order to test the prototype MET it is first biased to its operating point using the neodymium toroidal magnet. Fig. 3 is a plot of the lock-in amplifier output versus time as the position of the toroidal magnet is varied. Since the lock-in amplifier output is proportional to #$_{!"}$, the plot shows the ability to magnetically bias the MET to its proper operating point. Once at its operating point, the conductivity of the superconducting bridge is then modulated by applying a signal current to the solenoid, $$_{!"\#}$.

As expected, when the toroidal magnet is out of position, such that the MET is no longer at its operating point, varying $$_{!"\#}$ does not have an effect on #$_{!"}$. Fig. 4 indicates the conductivity of the superconducting bridge is being modulated via $$_{!"\#}$ by varying $$_{!"\#}$. Increasing $$_{!"\#}$ leads to increase in $$_{!"\#}$, which results in a bigger change in #$_{!"}$.

Fig. 3. I-V Curves showing intermediate states of MET as a function of magnetic field - a necessary step in validating MET performance.

Fig. 4. Lock-In Amplifier output representing the voltage equivalent of #$_{!"}$ for different values of solenoid supply current $$_{!"\#}$.

III. Conclusion

In this paper we have introduced the concept of the Meissner Effect Transistor (MET) and presented its theory of operation. Initial test results are shown to be consistent with the underlying theory. Further characterization of MET performance compared to theory will require a dedicated device run and an improved test set-up.

References

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