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Analytical model for the calculation and optimisation of cryogenically cooled current leads and wire interconnects

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The study of heat transfer in conduction cooled current leads and digital electronic interconnects is of vital importance during the design of cryogenic electronic systems where the cost of cooling increases exponentially as temperature decreases. It is a thermally complex problem that combines heat transfer due to conduction between the hot and cold ends of the leads, as well as the Joule heating effect generated by the current flow within. This is especially important when high power delivery is required (1W per wire, for example) to a cryogenically cooled system. The problem is often simplified by the application of the Wiedemann-Franz law, which states that the ratio of the electronic contribution of the thermal conductivity (κ) to the electrical conductivity (σ) of a metal is proportional to the temperature (T)[1], κ/σ=LT. Where L is a proportionality constant known as the Lorenz number. This is an empirical law that holds relatively well for most metals and has been shown to work well at high or very low temperatures (a few Kelvin), but not necessary in between [2]. The law has been used to derive the thermal analytical model that describes the minimum heat flux to be dissipated at the cold end of the current leads Q_min|*(L/A=opt)=I√(L_0 (T_hˆ2-T_lˆ2)) [3], where L is the length of the lead and A is its cross-sectional area. However, at cryogenic temperatures (4.2K to 300K) the Wiedemann-Franz law loses precision, and a more general approach must be taken. By taking into account the individual temperature dependance of the thermal conductivity and electrical resistivity of the metal, one can calculate the minimum heat flux for all metals at all temperatures, Q_min|*(L/A=opt)=I√(2∫_(T_c)ˆ(T_h)κρdT). This model, though more generally applicable, still has certain limitations to its usefulness. Firstly, it is only valid for an optimal L/A, which though preferable as it minimizes the heat flux that must be extracted, is not always possible due to other constraints during the design process. It also does not provide information regarding the temperature distribution along the length of the leads. Thus, in this paper a general case, 1D analytical model is proposed that describes the temperature distribution along metal wire interconnects between digital electronics at different temperature levels. This model can be applied to the design of cryogenic electronics systems where the accurate measurement of heat flux is crucial, such as cryo-CMOS, superconducting electronics, and quantum computers. As it is a general case model, it can be used to optimise the geometry of the leads, but it can also determine the feasibility of non-optimal systems by calculating the temperature distribution along the lead length. This will provide critical information regarding the increase in heat flux at the cold end above the minimum, as well as the value of T_max and its position between T_h and T_c. The new model can also handle non-uniform Joule heating along the length of the lead, as is quite common in microwave power distribution systems with some amount of impedance mismatch. The model has initially been validated by comparisons with the direct solution of the second order differential equations and will later be validated through experimentation.

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