FREE ELECTRON GAS PRIMARY THERMOMETER WITH A PPM ACCURACY

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Abstract: In the free electron gas primary thermometer the temperature is extracted by probing the energy distribution of its free electrons, which according to the Fermi-Dirac statistics is exponentially dependent on the electron gas temperature. The probing is done studying the dependence of the collector current of a bipolar junction transistor on the emitter-base forward bias. The temperature is extracted processing this current through a rigorous mathematical method. Here it is shown that carefully handling the experimental setup an accuracy in the order of the PPM can be achieved at the water triple point and better at the Gallium melting point.

1. INTRODUCTION

Gas thermometry is an old very well-known and widely used method of determining temperatures in certain range. The basic relationship on which gas thermometry is based is

$$pV = NRT[1 + B\frac{N}{V} + ...] \qquad (1)$$

where p is the pressure, V the volume of gas container, N is the number of moles of gas, R the molar gas constant, B, a virial coefficients, etc. and T the thermodynamic temperature of the gas. The measure of the temperature by this method results complicated by several gas intrinsic parameters as the virial coefficients, by the difficulty to establish the exact value of the volume, the adsorption of gas molecules on the vessel walls, etc. A free electron gas does not have any of those drawbacks; as all electrons are identical, and are not adsorbed on the walls of the material to which they belong. Because of these and other advantages it is highly desirable to have a thermometer based on a gas of free electrons. This research group has been working on the development of such a thermometer and published results which demonstrate that it is at reach of the current ordinary technology of the semiconducting materials and its devices. Improve the achieved accuracy requires of purposely designed bipolar junction transistors [1]. However, here it will be shown that by the careful management of the experimental setup necessary to this thermometer using ordinary commercial transistors an accuracy in the range of a few parts per million (PPM) can be easily attained.

2. THEORY; ELECTRONS IN THE SEMICONDUCTORS AND BIPOLAR TRANSISTOR COLLECTOR CURRENT

In a free electron gas, as that in the conduction band of a semiconducting material, the energy distribution of its electrons is given by the cuasi-exponential Fermi-Dirac statistics (**FD**). However, for energy levels several kT (k is Boltzmann´s constant and T the temperature) above the corresponding Fermi level; E_f, that energy distribution becomes simply exponentially dependent on the energy and the free electron gas temperature. Then, considering the **FD** statistics it results that in the conduction band of a semiconductor, the free electron concentration, n'_{n0}, having energies $E \geq E_C + E_0$, where E_C is the bottom of the conduction band and E_0 any arbitrary energy value, is given by

$$n'_{n0}(T) = n_{n0} e^{\frac{-E_0}{kT}} \qquad (2)$$

whith n_{n0} is the total concentration of electrons in that band.

Then, if for any given free electron gas at any temperature T_0, somehow an electrical current I_C, proportional, not to all the free electrons in the conduction band but, only those having $E \geq E_C + E_0$, such current will be given by

$$I_C(E_0,T) \propto n_{n0}(T)e^{\frac{-E_0}{kT}} \tag{3}$$

which means that such current actually constitutes a probe of the energy distribution of the free electrons of the gas. If additionally $\boldsymbol{E_0}$ can be fixed externally, from such current behavior as a function of $\boldsymbol{E_0}$, the electron gas temperature can be extracted.

Actually, the model of Shockely for the bipolar transistor, establishes that its collector current as a function of the external emitter-base forward bias, $\boldsymbol{V_{EB}}$, when >3kT and keeping short-circuited the base-collector junction, is given by [2]

$$I_C(V_{EB},T) = An_{n0E}e^{\frac{-E_{EB}}{kT}}e^{\frac{qV_{EB}}{kT}} = I_{C0}(T)e^{\frac{qV_{EB}-E_{EB}}{kT}}$$

$$I_C(V_{EB},T) = I_{C0}(T)e^{\frac{-E'_0}{kT}} \tag{5}$$

where *A* is a parameter intrinsic to each transistor, even if of the same family, $\boldsymbol{E'_0} = \boldsymbol{E_{EB}} - \boldsymbol{qV_{EB}}$, is the externally controllable energy barrier that determines which electrons participate to the conduction of the electric current, with $\boldsymbol{E_{EB}}$ a constant; the emitter-base energy barrier. Clearly $\boldsymbol{E'_0}$ is externally controlled. Then, this current constitutes a probe of the free electron energy distribution, corresponding to Eq. (3), from which the free electron gas temperature can be obtained.

The mathematical method to extract the temperature of the free electron gas of the transistor has been widely presented and discussed [1].

3. RESULTS

Experimental measurements to obtain $\boldsymbol{I_C(V_{EB}, T_0)}$ data were done using off the shelf commercial Silicon bipolar transistors at thermal equilibrium with a water triple point cell (***TWP***) and with a Gallium melting point cell (***MPGa***). The collector current vs $\boldsymbol{V_{EB}}$ was measured using an HP4145 Semiconductor Parameter Analyzer. The version of this equipment used here has four independent current amplifiers. Then, before proceeding to the measurement of the transistors the amplifiers were carefully studied to determine the one displaying the best performance.

In this study ordinary commercial transistors were used, although carefully chosen, taking in account their impurity distribution at each region; Emitter, Base and Collector. They were also ordinary packaged, i. e., in a black plastic, whose thermal characteristics are not available. Then, a particular measurement procedure, which will be fully described in this presentation, was observed. Our results show, that an accuracy around a few parts per million, can be reached.

4. DISCUSSION

Our study shows that, as anticipated by the theory, the performance of the current amplifiers used to measure the current in this thermometer is critical as well as the procedure to realize the current voltage measurements. When all of this is taken into account, the accuracy achievable using ordinary commercial transistors can be in the range of a few parts per million.

5. CONCLUSIONS

In conclusion this study has proven that ordinary inexpensive bipolar junction transistors can be at the origin of a new type of high performance, extremely inexpensive primary thermometers displaying high accuracy.

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