Operational Amplifiers in the Temperature Range from 300 to 4 K

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In this paper the amplifying properties of operational amplifiers (bipolar, Bi-FET and CMOS) in the function of temperature are presented and discussed. We measured operational amplifiers between 300 K and 4 K. The Bi-FET opamps work well in the temperature range down to 60-70 K. The CMOS operational amplifier (type of AD8594) operate correctly in the whole temperature range from 300 K to 4 K.

INTRODUCTION

Operational amplifiers are structural elements of many analog circuits. The ability of the above circuits and devices to work properly in a large range of environment temperature depends on the thermal properties of opamps. The low temperature range is divided into three sub-ranges: from 0 °C to −50 °C (from 273 K to about 220 K), from 220 K to 77 K and below 77 K. In this sub-range bipolar devices do not operate.

According to catalogue data, the sub-range below 220 K is no longer the nominal work range for operational amplifiers. The operating temperature range is limited because operational amplifiers consist bipolar transistors. Literature studies show that bipolar transistors are not able to operate at 77 K and below [1]. The authors of various papers state that at 77 K the current amplification factor β of commercial bipolar transistors is close to 1 or at most not greater than 10-20. There exist some exceptions. There were presented bipolar transistors manufactured by polyemitter bipolar processing technology, for which β even increases with the decrease of temperature from 300 K to 77 K [2]. The second exception is a bipolar transistor with a tunnel MOS emitter and an induced base [3].

However, many technical instruments should work in the low temperature range. Control systems and communications systems of aircraft and spacecraft must work at temperatures below 220 K, as well as meteorological instruments and a number of instruments in low temperature physics. In our research we considered commercial operational amplifiers. We determined an open-loop gain and an offset of input voltage in the function of temperature in the range from 300 K to 4 K. The aim of the research was to determine the lower limit of work temperature for all types of operational amplifiers.

Bi-FET AMPLIFIERS

Operational amplifiers always include bipolar transistors in their structure, because of the large value of amplification of the latter. Bi-FET opamps consist of an input stage with field effect transistors and of the remaining stages with bipolar transistors. Figure 1 shows amplification properties of a bipolar transistor (BC108C) and a FET transistor (BF245B) in the function of temperature. We measured a transconductance g_m for the FET because a value of g_m describes amplification of a JFET transistor.

$$g_m = \mathrm{d}I_D/\mathrm{d}V_{GS}$$

After cooling down the JFET from 300 K to 77 K its transconductance g_m increases twice (Fig. 1, left). We measured a β-coefficient of current amplification of the bipolar transistor BC108C (Fig. 1, right). The current amplification decreases from 600 at 300 K to 7 at 77 K.

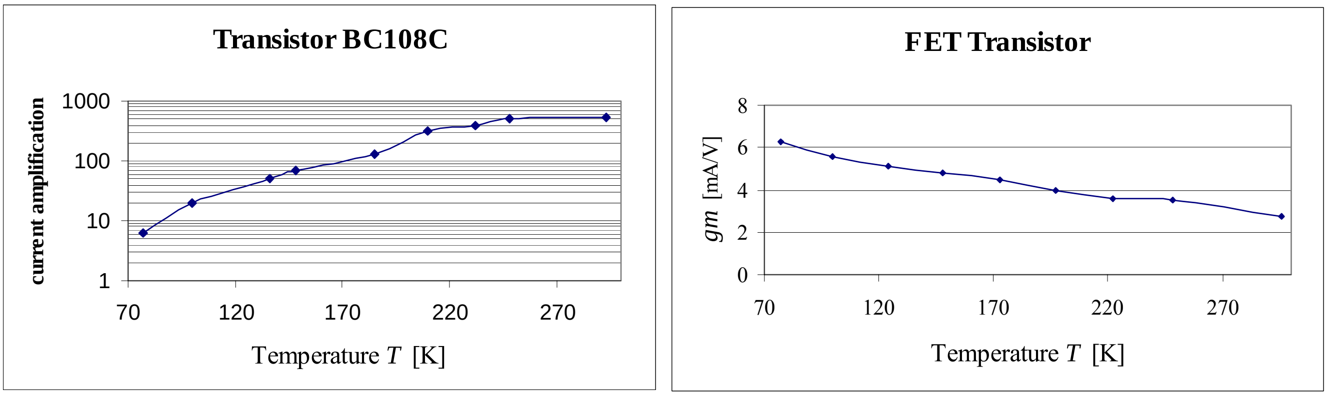

Figure 1 Amplification properties of transistors in the temperature range 77-300 K. At left: a transconductance g_m of FET transistor BF245 (on the right); a current amplification β of a bipolar transistor.BC108C (on the left)

We constructed and tested a 2-stage Bi-FET amplifier with the transistors described above. The amplifier circuit is presented in Fig. 2 (left). A bias of a base circuit of a bipolar transistor is realised using two diodes. Such method of a bias can stabilised a collector current in a bipolar transistor. A voltage gain of the amplifier is shown in Fig. 2 (right). The gain of the amplifier varied from 56 V/V to 80 V/V in the temperature range 77-300 K. The gain is satisfactorily constant for many applications. An input impedance of the Bi-FET amplifier is rather high because of a FET transistor in the input stage of the amplifier.

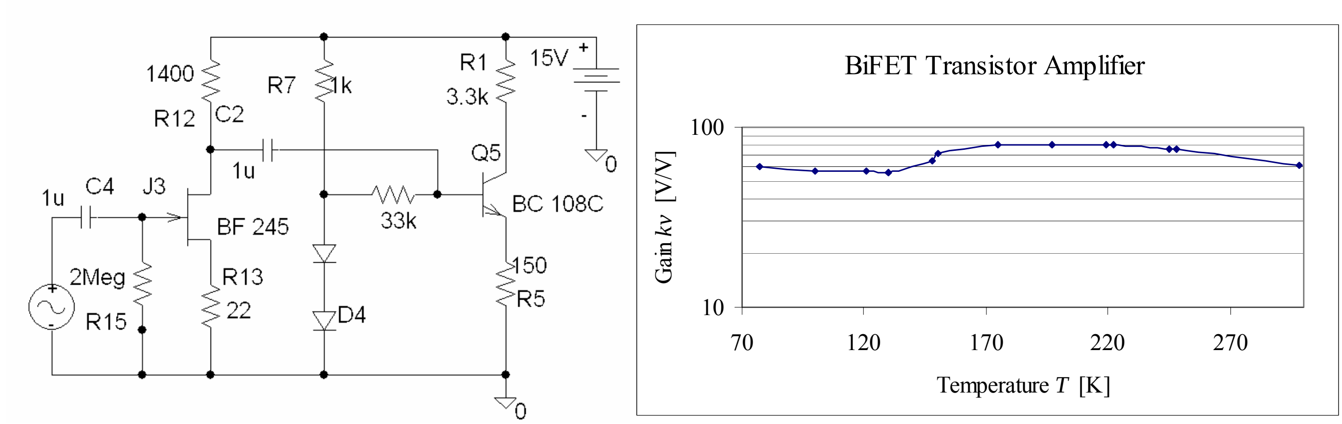

Figure 2 A circuit of the Bi-FET amplifier (left) and its voltage gain in the range 77-300 K (right)

BIPOLAR AND BI-FET AMPLIFIERS

Bipolar operational amplifiers

We took a general purpose operational amplifier µA741 and a ultralow noise operational amplifier AD797 (manufactured by Analog Devices) for investigation. We studied the amplification factor and the offset voltage of opamps in the function of temperature in the range from 293 K to 77 K. We assumed 100% amplification at room temperature. For all opamps examined, the amplification factor decreases steadily with the decrease of temperature below 150 K. Below 100 K the amplification factor decreases sharply and reaches a zero value. The offset of input voltage slightly changes in the temperature range from 293 K to about 100 K and increased sharply below 100 K.

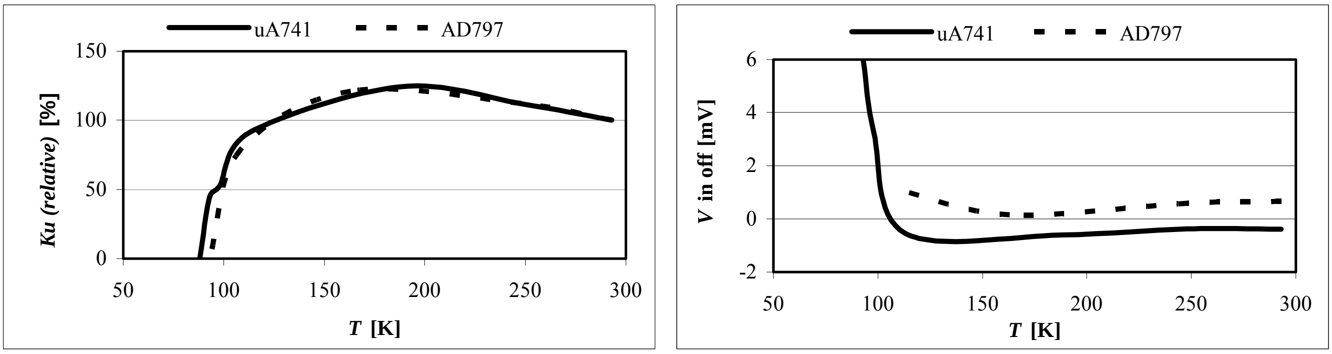

Figure 3 A relative amplification factor (on the left) and an offset of input voltage (on the right) in the function of temperature for two types of bipolar opamps (μA741 and AD797)

BiFET operational amplifiers

Bi-FET operational amplifiers show similar temperature properties to bipolar amplifiers. We investigated two types of Bi-FET amplifiers: TL082 (made by Texas Instruments) and LF411 (made by National Semiconductor). The same parameters, i.e. the amplification factor of an open-loop amplifier and the offset of the input voltage, were measured for Bi-FET opamps in the function of temperature. In the whole temperature range the opamps examined preserve their amplification properties. The relative amplification factor decreases from 100% at 293 K to about 40% at 77 K – Fig. 4. The maximum of the function K_u = f(T) at about 100-150 K results from the highest mobility of electrons in silicon in this temperature range. The actual temperature at which the amplification is equal to 0 falls in the range 50 K – 70 K and differs for different samples of opamps. The offset of input voltage slightly changes in the temperature range from 293 K to about 100 K and decreased dramatically to −300 mV below 100 K.

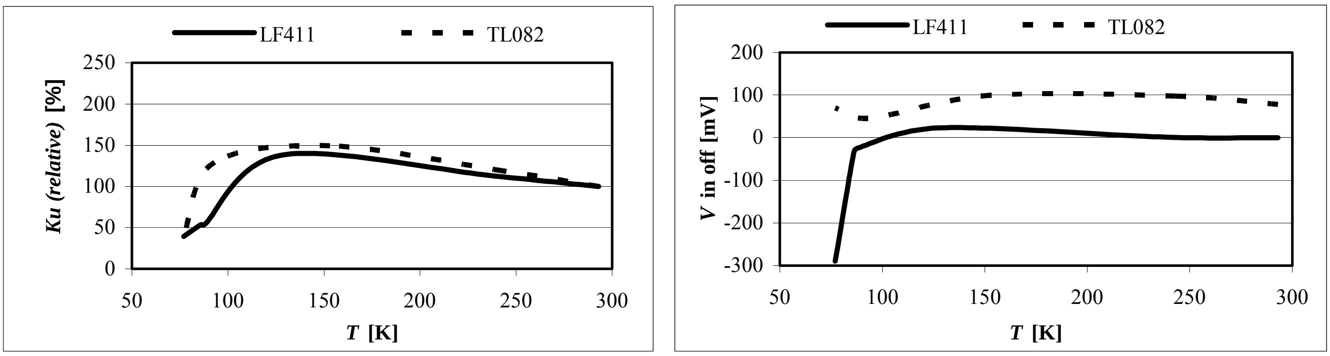

Figure 4 A relative amplification factor (on the left) and an offset of input voltage (on the right) in the function of temperature for two types of Bi-FET opamps (TL082 and LF411)

We also noticed some fluctuations of the offset voltage of the order of 1 mV. These fluctuations might be due to temperature fluctuations of the device environment. We must note that the introduction of a negative feedback component in the opamp circuit reduces dramatically the influence of the offset voltage on the output voltage.

CMOS OPERATIONAL AMPLIFIERS

We investigated an analog CMOS IC at low temperatures. It is known that CMOS digital integrated circuits are able for an operation in liquid He. We investigated an operational amplifier of a type of AD8594 (manufactured by Analog Devices) in the temperature range from 300 K to 4 K. The AD8594 device consists 4 operation amplifiers in one chip. According to catalogue data of AD8594 opamps the operating temperature range is −40 °C to +85°C, the junction temperature range is −60 °C to +150 °C, an offset of input voltage is 25 mV (maximal), a gain bandwidth product is 3 MHz (typical) – [4]. We measured two parameters: an open-loop gain and an offset of input voltage in the temperature range down to 4 K. We determined the open-loop gain indirectly, from measurements of a gain bandwidth product at several temperature points. The operational amplifier operated with a negative feedback (the gain with a feedback is of 500 V/V. The results of the measurements are presented in Fig. 5.

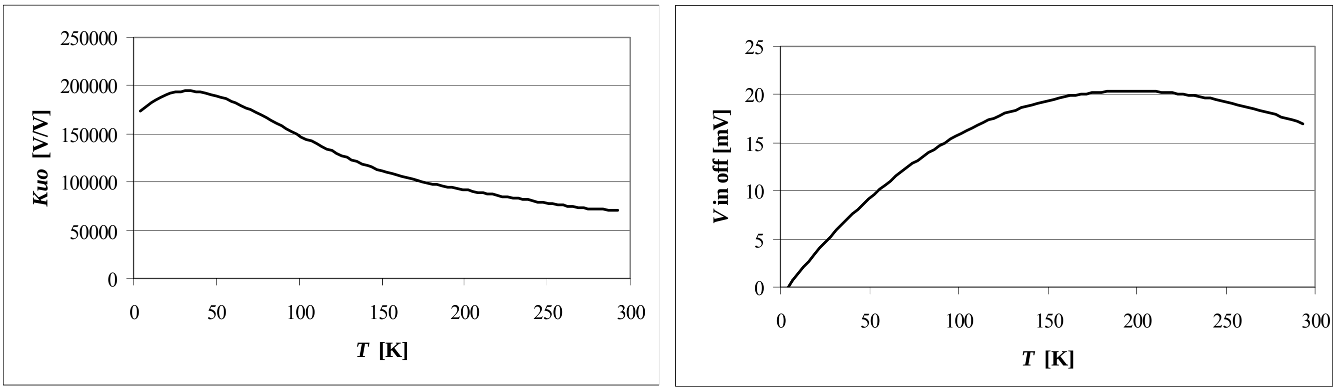

Figure 5 An open-loop gain (on the left) and an offset of input voltage (on the right) in the function of temperature for CMOS opamp of AD8594 type

CMOS opamp AD8594 not only keep its amplifying ability down to 4 K but its amplification factor is even greater at 4 K (open-loop gain is of 19×10^4 V/V) than at 300 K (open-loop gain is of 7×10^4 V/V). The offset of input voltage decreases below 200 K. Its value approaches zero at 4 K.

CONCLUSIONS

For bipolar operational amplifiers the amplification drops to zero at the environment temperature of about 90 K. Bi-FET operational amplifiers keep good amplifying properties in the range down to about 70 K. The CMOS operational amplifiers AD8594 not only keep its amplifying ability down to 4 K but its amplification factor is even greater at 4 K than at 300 K. It is possible to use CMOS operational amplifiers for instruments operated in a liquid He bath.

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