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MEASUREMENT OF THE TEMPERATURE INSIDE STANDARD INTEGRATED CIRCUITS

ABSTRACT *The paper describes method of temperature measurement of standard integrated circuits based on the data from the chip datasheet. Described temperature sensing technique uses built-in ESD protecting diodes. Some tests on LM741 operating amplifier were done. Results were compared with other temperature measurement methods.*

Keywords: *temperature sensing, ESD, integrated circuits.*

1. INTRODUCTION

Increasing power dissipation at the limited area of the integrated circuit is often cause of its damage or at least errors in its behaviour. As an effect thermal issues of the circuit work must be considered. Some real-time temperature monitoring systems for ASICs (Application-Specified Integrated Circuit) have been developed [2]. It is possible to built-in temperature sensors

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into integrated circuit and use information if chip temperature to control the chip. There are also some methods to measure temperature of surface of chip package. The problem is how to measure temperature of the silicon die inside the chip when there is no built-in temperature sensing device in standard chip available on the market.

Inaccuracy of the theoretical calculations disqualifies this method of temperature measurement what will be proved later. Usage of external temperature sensors can give only information of chip surface temperature. Consequently another method have to be introduced.

The paper describes usage of ESD protecting diodes, available inside most of the integrated circuits, to sense the temperature inside the chip. Next sections will provide more details about the method. In addition some tests on standard LM741 operational amplifier were done to verify the method. Other methods were also used to measure the chip temperature to compare the results.

2. TEMPERATURE MEASUREMENTS

Many different temperature sensing techniques have been developed. Some of them are very sophisticated but all of them have advantages which made them useful for a specific applications while the same features for another applications could cause problems.

In first approach the chip temperature can be estimated from the theoretical value T_{theory}. It can be calculated from commonly known equation (1):

$$T_{theory} = T_A + \theta_{JA} P_D \quad (1)$$

where T_A is ambient temperature, P_D dissipated power and θ_{JA} is junction-ambient thermal resistance. All of this data are known for a specific application and from the chip datasheet. It could be concluded from equation (1) that the temperature of the not working circuit is equal to ambient temperature and can not be lower. Furthermore, the temperature is increasing with greater power consumed by the chip. The problem is that thermal resistance is usually an approximated value. For example for DIP packages general datasheet θ_{TA} value is 100°C/W. It can be fairly assumed that this is not an exact value. Practical tests shown that thermal resistance read from datasheet is far from the realistic one.

Another solution to measure the chip temperature is usage of silicon temperature sensors inside the chip. There are many existing dedicated diodes or P-N junctions which act as a temperature sensors in various integrated circuits technologies. Some more complex structures could also be used. A PTAT (Proportional To Absolute Temperature) sensor with a linear thermal characteristic is a good example of such a circuit [3]. This solutions are important because they indicate the temperature inside the chip package or directly the silicon die temperature. But they could not be used for every application. Only designer of ASICs can afford to use this sensors if there is enough area available inside the chip. In case of standard chips available on the market there are usually no such sensors inside the package and usage of this method is simply impossible.

If the engineer have to deal with a temperature measurement of the standard integrated circuit usage of external sensors is an alternative option. Another circuit for sensing temperature can be mounted on the chip package or other devices (such as pyrometers or infrared cameras) can be used. Results of these measurements (e.g. pictures taken by infrared camera) could be useful for further data processing. Several methods for processing thermograms [4] have been introduced and they make interpretation of results very easy. However, these solutions have to deal with a problem of heat transfer from inside the chip to package surface and to the ambient. Indicated temperature is a value measured on external border of the package, not of the silicon die inside it.

None of mentioned methods allows to measure the temperature of the silicon die inside the package. The problem is important because some applications need information of temperature directly inside the chip, not its surface. If there is a need to know the temperature inside the standard integrated circuit another method have to be used.

3. ESD DIODE USAGE

It is well known that voltage at every diode, not only at dedicated to temperature sensing ones, is dependent on temperature. Even if there is no sensor inside the package almost every standard chip has ESD and input protecting diodes which can also be used [1]. What is important these diodes are not used in normal work of the circuit. Structure of typical protecting diodes in operational amplifier is presented in Fig. 1. Diodes connected to VDD and GND ports are protecting from ESD (ElectroStatic Discharge) while diodes between inputs are protection from reverse voltage breakdown. These diodes, except their primary functions, can also be used as a temperature sensors.

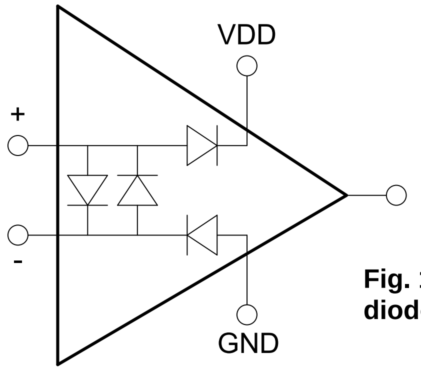


Fig. 1. Standard structure of ESD and input protecting diodes in operational amplifier

Usage of protecting diodes inside standard integrated circuits can be sometimes complicated. Manufacturers often do not publish structure of the chip inside the package. In order to use presented method based on ESD diodes some additional tests have to be done to investigate structure of the protecting diodes and ensure that the method will not damage core of the chip.

The phenomenon of measuring temperature with diodes is based on the fact that with constant current applied to the diode voltage across it is decreasing with a slope of 1 to 2 mV/°C. As an effect thermal characteristic of used diode has to be known before measuring the temperature. To collect it circuit shown in Fig. 2 and a thermal chamber can be used. Value of I_S from the current source should not be too high to prevent self heating of the diode. In presented case diode between non-reversing input and VDD port has forward polarization and diode voltage V_D should depend on temperature.

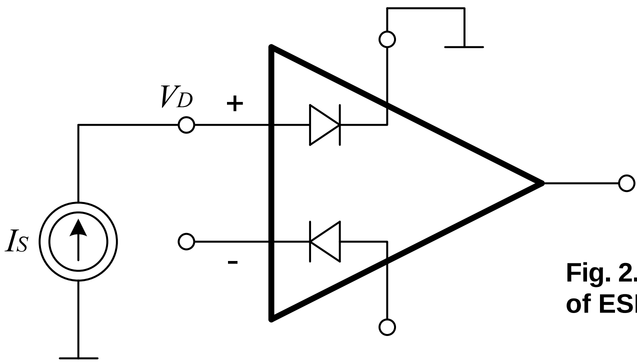


Fig. 2. Block diagram for thermal calibration of ESD protection diode

It is sufficient to collect only three values of V_D at different temperatures to sketch the thermal characteristic of the diode. But measuring greater number of points will determine better accuracy.

If the thermal characteristic of the diode is already known the circuit can work in its standard application. When the temperature measurement is needed it is necessary to switch it to the calibration configuration and collect V_D. Value compared with the characteristic will give the present silicon die temperature.

Accuracy of the measurement depends only on precision of used voltmeter and approximation of the diode thermal characteristic. Simplicity of the measurement methodology is important advantage of presented method.

Presented method needs some additional work to prepare thermal characteristic of the diode but ensures that temperature measurement is possible with almost every standard integrated circuit available on the market. Moreover, the ESD diodes are located inside the package or directly on the silicon die so gathered results are more accurate than any external measurements.

4. TESTS

To verify presented method some test with standard LM741 operational amplifier were done. The choice of the test circuit was caused by need of very simple and frequently used by engineers circuit. LM741 is well-known and popular construction which well suites measurement needs.

At the first step thermal characteristic of the ESD protecting diode has been gathered, Fig. 3. The chip was placed in thermal chamber for a few minutes at every temperature point so the silicon die inside the package could reach desired temperature. Applied I_S from the current source was equal to 1,5 mA which is quite small value and should not be source of excessive diode heating. Collected characteristic was approximated for a temperature range from 10 to 100 C. This range covers the temperatures which can be expected while amplifier work. The voltage across diode can be described by (2). The characteristic slope of -1,7 mV/°C confirms previous theoretical assumptions.

$$V_D = -0{,}0017T + 0{,}745 \qquad (2)$$

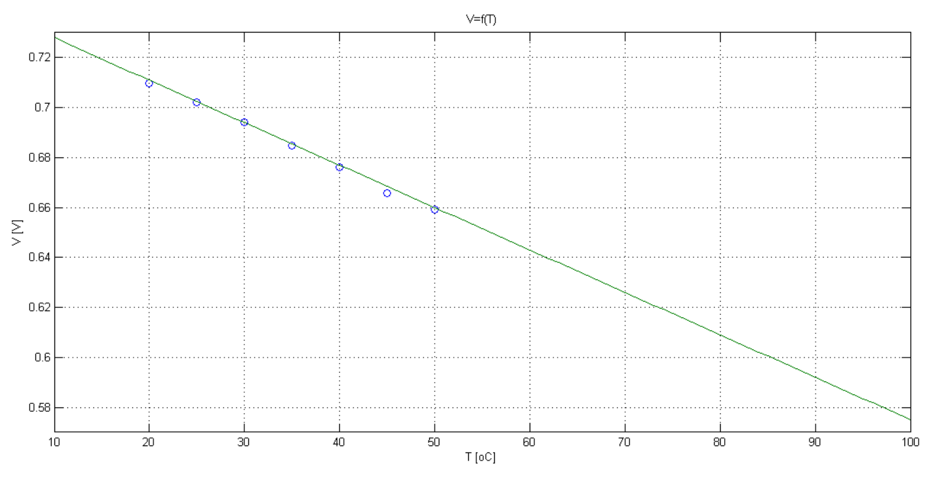


Fig. 3. Voltage drop at the LM741 ESD protection diode for temperatures from 10 to 100°C

After calibration the amplifier was used in simple voltage follower application presented in Fig. 4. Total power dissipation resulting from the R_L load and quiescent current was 175,6 mW. That means that based on (1) and assuming thermal resistance θ_{JA} from LM741 datasheet equal to 100°C/W [5] and ambient temperature T_A equal to 24°C chip temperature should be about $T_{theory} \approx 51{,}6$°C.

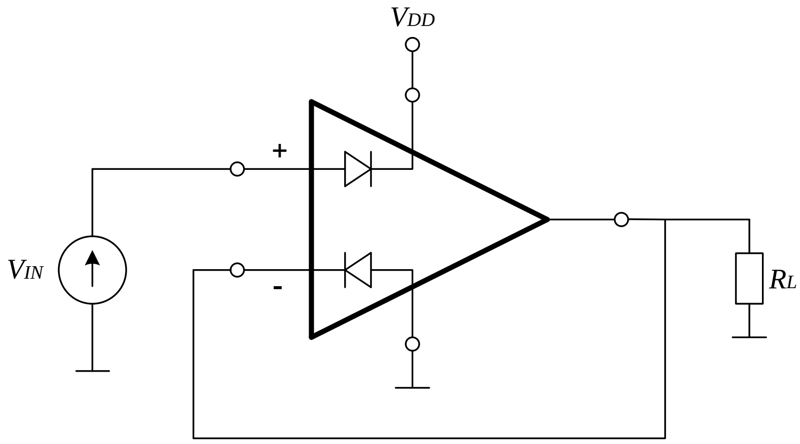


Fig. 4. Block diagram of the operating amplifier test application

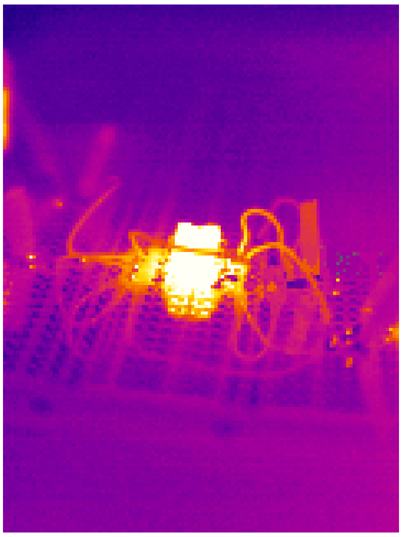
Theoretical result was verify by some practical methods. Pyrometer measurement showed that temperature of the chip package was approximately equal to $T_{pyrometer} \approx 64$°C. Usage of pyrometer is characterized by good accuracy and can be a reference value of the chip surface. Measured value of the package temperature is typical for integrated circuits in standard applications.

Another test was performed with an infrared camera which gives less accurate result but obtained thermograms are easy in interpretation. Picture taken with infrared camera (Fig. 5) indicated temperature equal to $T_{camera} \approx 63{,}5$°C.

Both of previous results are much higher than theoretical expectation. The cause is most probably previously mentioned problem with thermal resistance exact value. Based on the measured temperatures it can be assumed that proper value of θ_{JA} of the tested chip should be about 222 °C/W and can be different for every package series. This inaccuracy disqualifies method of theoretical calculation because thermal resistance of every single chip can not be measured before circuit usage and calculations with wrong θ_{JA} value are source of serious errors. At this stage of tests exact value of temperature inside the chip package is still unknown.

Final verification of the chip temperature included usage of ESD protecting diodes. The chip was switched from the follower application to calibration structure of the circuit and value of the voltage across diode was about $V_D \approx 0{,}635$ V. Based on the equation (2) from the diode calibration and temperature characteristic of the diode the temperature inside the chip should be $T_{diode} \approx 64{,}5°C$. This value is only a half degree higher than collected by other means of measurement. The result is understood because surface of the chip should be a little cooler then its inside.

Fig. 5. Picture of the chip during tests taken with infrared camera



Presented results proved that ESD protecting diodes can be used to sense the temperature directly inside package of standard integrated circuits with good accuracy.

5. CONCLUSIONS

In the paper a method of internal chip temperature measurement with ESD protecting diodes usage has been explained. A simple application with LM741 has been designed for verification purposes. A method is characterized by good accuracy of the measurement result. Main disadvantage of the described method is the necessity to calibrate the diode before temperature measurement. After this additional work the methodology of measuring temperature is very simple.

Other sensing methods (pyrometer, infrared camera) gave similar temperature values. That means that results obtained with ESD protecting diodes are proper. Only the theoretical calculation resulted with irregular temperature. The most probable cause is inaccuracy of the thermal resistance value given by the datasheet of the operational amplifier. As an effect a proper value of θ_{JA} for the tested LM741 has been deduced. All measured temperature values have been gathered and compared in Tab. 1.

TABLE 1
Chip temperature for different measurement methods

Measurement method	Temperature [°C]
Theoretical value T_{theory}	51,6
Pyrometer $T_{pyrometer}$	64
Infrared camera T_{camera}	63,5
ESD diode usage T_{diode}	64,5

As has been proved presented method is suitable to measure internal temperature of an integrated circuit. What is important, almost every standard chip has protecting diodes inside the package so the method can be applied to most of the circuits. The accuracy of the measurement depends on used equipment and in presented case is satisfactory for the test purposes.

LITERATURE

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POMIAR TEMPERATURY WEWNĄTRZ STANDARDOWYCH UKŁADÓW SCALONYCH

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STRESZCZENIE *Praca opisuje metodę pomiaru temperatury wewnątrz obudowy standardowych układów scalonych z wykorzystaniem danych z noty katalogowej układu. Przedstawiona technika rozpoznawania temperatury oparta jest o wykorzystanie wbudowanych w układ diod zabezpieczających przed wyładowaniami elektrostatycznymi. Dla potwierdzenia przydatności metody wykonano testy z wykorzystaniem wzmacniacza operacyjnego LM741. Wyniki zostały porównane z innymi metodami pomiaru temperatury.*