A Semiconductor Device Thermal Model Taking into Account Non-linearity and Multhipathing of the Cooling System

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Abstract. The paper is devoted to modelling thermal properties of semiconductor devices at the steady state. The dc thermal model of a semiconductor device taking into account the multipath heat flow is proposed. Some results of calculations and measurements of thermal resistance of a power MOSFET operating at different cooling conditions are presented. The obtained results of calculations fit the results of measurements, which proves the correctness of the proposed model.

1. Introduction

Ensuring effective cooling of electronic components is one of the most important challenges the designers and constructors of electronic and power electronics devices are facing. The designer usually has information about the estimated value of power dissipated in discrete electronic components and the imposed restrictions concern, e.g. a permissible value of input power from the power source and the maximum size and shape of the system casing. Under these conditions, the cooling system components are often intuitively chosen. The selection of components of the heat flow path is complicated and difficult due to multipath heat transport from the die to the surrounding [1, 2]. In order to determine thermal properties of the electronic components, their thermal models are formulated. The structure of such a model, taking into account the multipathing heat transport is shown in figure 1 [2].

As you can see, the heat can flow in various ways, using three mechanisms of its transfer: conduction, convection and radiation. Since the description of the phenomena associated with the heat flow is very complex, the practical verification of the design of the cooling system is made experimentally by constructing a prototype. This often results in long time designing or oversizing significantly cooling system components, leading to an unjustified increase in the cost of the device.

The commonly used thermal models have a form of the electric circuit based on the electric-thermal analogy [3 - 6]. Most frequently the elements of the heat transfer path, indicated in figure 1, are represented by the RC network of the Cauer or Foster structure [3 - 6]. Due to the dependence of the parameters describing the heat flow through each element of the path of the heat flow on temperature, the thermal model is generally non-linear [3]. The values of resistances and capacitances existing in the thermal model are typically obtained from the measurements realised with the use of optical or electrical methods [7- 11]. Many papers, for example [8 - 14], present the results of measurements of the thermal resistance of semiconductor devices, in which the influence of the power dissipated in the investigated device and the construction of the cooling system of this device on its

thermal resistance is clearly visible.

In the literature, such as [15 - 19] only the selected aspects of modelling the thermal behaviour of electronic components are considered. Moreover, empirical formulas describing dependencies of the device transient thermal impedance on the dissipated power for one chosen cooling condition of the device are described [3].
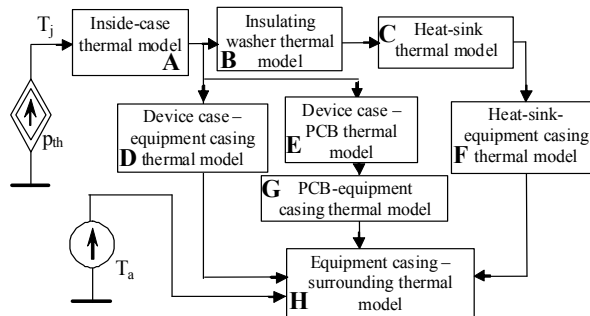

Figure 1. General form of the thermal model of a semiconductor device constituting a component of an electronic device mounted in the casing.

In this paper, which is an extended version of the paper [13], thermal properties of the circuit consisting of the power transistor mounted on the aluminium heat-sink with insulating washer and the Peltier module are analysed. Additionally, the thermal properties of this transistor operating without any heat-sink or located on the heat-sink without the Peltier module are considered.

In section 2 the measurement setup used to measure the thermal parameters of semiconductor devices is presented. The form of the thermal model is described in section 3. Section 4 presents the results of investigations of the power MOS transistor operating at different cooling conditions.

2. Measurement setup

The results of measurements presented in this paper are obtained by means of the electric method of measurements of transient thermal impedance using the cooling curve [11, 20]. The voltage on the forward biased body diode is used as a thermally-sensitive parameter. The measurements were realised in the authors' measurement setup, described in the paper [12]. The block diagram of this measurement setup is shown in figure 2.
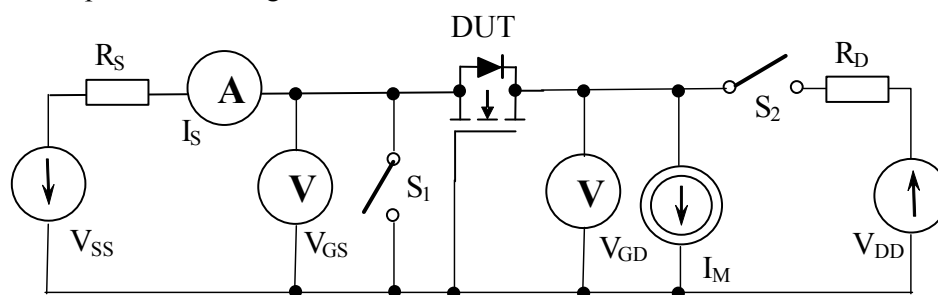

Figure 2. Block diagram of the measurement setup.

In the presented measurement setup, the examined transistor (DUT) operates in the common gate configuration. The source current is regulated by means of the voltage source V_{SS} and the resistor R_S, and its value I_S is measured by the ammeter. The value of the gate-drain voltage V_{GD} is regulated by the voltage source V_{DD}. The values of voltages V_{GS} and V_{GD} are measured by means of voltmeters. The measurement of thermal resistance is realised in 3 stages. First, the thermometric characteristic $V_{GD}(T)$ of the body diode at the forward current equal to I_M is measured. During the calibration the switch S_2 is off and the switch S_1 – is on. The value of the current I_M is equal to 10 mA. At this value of I_M the thermometric characteristic is linear [12]. In the second stage, the examined transistor self

heats as a result of dissipation of the power $P_H = I_S \cdot (V_{GS} - V_{GD})$ in it. This stage lasts until the steady state is obtained and the voltage V_{GS} practically does not change. In the third stage the transients of the voltage V_{GD} on the body diode are registered from the moment t = 0, in which the switch S_1 is turned-on and the switch S_2 is turned-off, until the steady state is obtained. The PC registers values of the voltage on the body diode and controls the switches S_1 and S_2.

On the basis of the measured time course $V_{GD}(t)$, the thermometric characteristic $V_{GD}(T)$ and the value of the power P_H at the end of the second stage of the measurement, the course of the transient thermal impedance $Z_{th}(t)$ is calculated using the following formula:

$$Z_{th}(t) = \frac{V_{GD}(t) - V_{GD}(T_a)}{P_H \cdot F}$$ (1)

where T_a denotes the ambient temperature and F - the slope of the thermometric characteristic $V_{GD}(T)$. The thermal resistance R_{th} is equal to the value of $Z_{th}(t)$ at the steady state.

Of course, it is possible to measure the value of the thermal resistance using any dc method, but the range of currents and voltages, in which this method could be used is strongly limited [8, 14].

3. Form of the thermal model

In the paper the cooling system of the power MOS transistor containing a heat-sink and a Peltier module is considered. The formulated dc thermal model of the considered system of the general form is shown in figure 3. In this model, the controlled current source G_{th} represents power dissipated in the modelled device, the voltage source V_{Ta} - ambient temperature, whereas non-linear resistors – thermal resistance of the components of the heat flow path.

On the basis of the dependencies specified by the producers describing thermal resistances of individual components of the heat flow path and the measurements made by the authors, the analytic expressions describing the dependence of the thermal resistance of individual components of the heat flow path are formulated.
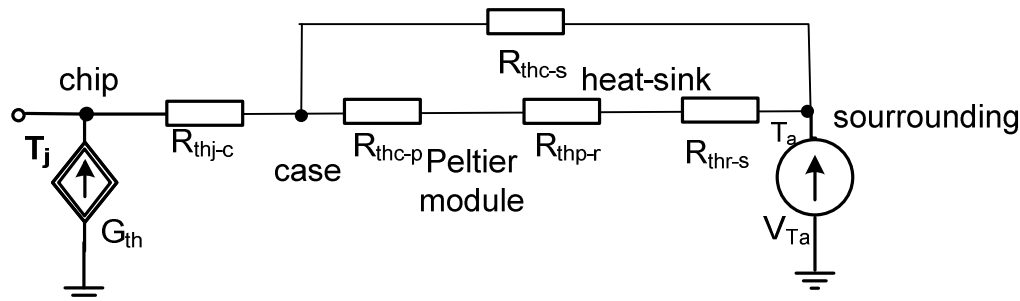

Figure 3. DC thermal model of a semiconductor device mounted on a heat-sink.

The thermal resistance R_{thj-c} is constant and its value is equal to the value given by the producer in the catalogue card. The values of the thermal resistance between the case and the surrounding R_{thc-s} is estimated from the measurements of R_{thj-a} of the transistor operating without any heat-sink as the difference between R_{thj-a} and R_{thj-c}.

In turn, the thermal resistance of the isolating washer R_{thc-a} is usually very small and with the correctly performed connection does not exceed typically 1 K/W. Therefore, in the thermal model one can arbitrarily accept the top value of this parameter $R_{thc-a} = 1$ K/W. The thermal resistance of the isolating washer can be given on the basis of the values of the thermal conductance and geometrical dimensions of the element case given by the producer or based on the measurements of the thermal resistance R_{thj-a} of the transistor mounted on the heat-sink for two cases: R_{th1} - without the isolating washer and R_{th2} - with such a washer. The difference $R_{th2} - R_{th1}$ is equal to the value of the thermal resistance R_{thc-a}.

As it was shown e.g. in [21, 22] the thermal resistance of the power transistor can change in an essential manner e.g. in the function of the pressure exerted on the washer isolating the heat-sink and

the device case. The value $R_{thj\text{-}a}$ of the examined device in the considered range of changes of pressure p changes even twice, but for the value of the pressure p higher than 1.2 N/mm^2, which corresponds to tight screwing of the screw, the thermal resistance is practically constant. Then, for the correctly performed connection of the device to the heat-sink the value of $R_{thc\text{-}a}$ is practically constant.

In turn, the thermal resistance between the heat-sink and the surrounding $R_{thr\text{-}s}$ can be obtained from the catalogue dependences of the thermal resistance of the heat-sink on its length. In the case, when such dependence is not accessible, the value $R_{thr\text{-}s}$ can be obtained on the basis of the measurements of the thermal resistance $R_{thj\text{-}a}$ of the transistor installed on the heat-sink. For this situation, typically the value of $R_{thc\text{-}s}$ is omissible high. In such a case the value $R_{thr\text{-}s}$ can be calculated from the dependence:

$$R_{thr-s} = R_{thj-a} - R_{thj-c} - R_{thc-p} - R_{thp-r} \qquad (2)$$

It should be taken into account that as it results e.g. from [12], the value of $R_{thr\text{-}s}$ depends on the spatial orientation of the heat-sink and the values of this parameter at different orientations of the heat-sink can differ from one another even by about 20%.

The value of the thermal resistance between the Peltier module and the heat-sink $R_{thp\text{-}r}$ can be obtained from the measurements of $R_{thj\text{-}a}$ of the transistor situated on the heat-sink for two cases: with the Peltier module R_{th3} and without the Peltier module R_{th4}. Then

$$R_{thp-r} = R_{th3} - R_{th4} \qquad (3)$$

The value $R_{thp\text{-}r}$ is a decreasing function of both the power p_{th} dissipated in the examined transistor and the power p_p supplying the module. Of course, on the basis of the measurements of the mentioned dependences it is possible to describe thermal properties of the selected Peltier module.

4. Results

In order to verify the correctness of the proposed thermal model, the measurements and calculations of the thermal resistance of the power MOS transistor IRF530 operating at different cooling conditions are performed. The considered thermal model has the form shown in figure 3. On the basis of the measurement performed by the authors, the following values of model parameters were estimated: the thermal resistance between the inside and the case in compliance with the catalogue card [23] is $R_{thj\text{-}c}$ = 1.9 K/W. The thermal resistance of the connection between the case and the heat-sink filled by silicone is equal to 0.5 K/W.

Several cooling system configurations are explored. In the simplest case, when the transistor operates without the heat-sink, its thermal resistance is a function of the dissipated power [3, 12, 13]. For the vertically situated transistor in the case TO-220, the dependence $R_{thc\text{-}a}(p_{th})$ can be described with the following empirical formula

$$R_{thrc-a} = R_4 + R_5 \cdot \left(1 - \exp\left(-p_{th0}/d\right)\right) \qquad (4)$$

For the considered cooling system the values of parameters in equation (4) are: R_4 = 44.8 K/W, R_5 = 8 K/W, d = 2.5 W.

For example, for the transistor situated on the heat-sink without the additional isolating washer the thermal resistance between the heat-sink and the surrounding $R_{thr\text{-}s}$ is non-linear, i.e. its value depends on the power p_{th} dissipated in the transistor according to the formula

$$R_{thr-s} = R_0 + R_1 \cdot \exp\left(-\left(p_{th} - p_0\right)/a\right) \qquad (5)$$

For the considered cooling system R_0 = 1.9 K/W, R_1 = 1.5 K/W, p_0 = 12 W, a = 8 W.

The operation of the transistor IRF530 separated from the same heat-sink through the Peltier module is also considered. The thermal resistance of the connection between the case of the device and the module is 0.5 K/W. In turn, the thermal resistance of the Peltier module depends both on the temperature difference between its both sides, and hence on the power p_{th} dissipated in the examined device, and on the power p_p supplying the Peltier module. The thermal resistance $R_{thp\text{-}r}$ is described by the formula

$$R_{thp-r} = R_2 + R_3 \cdot \exp\left(-p_p/b\right) + R_4 \cdot \exp\left(-\left(p_{th} - p_1\right)/c\right) \qquad (6)$$

For the considered transistor, the values of the parameters in the equation (6) are as follows: $R_2 = 4.7$ K/W, $R_3 = 1.8$ K/W, $R_4 = 1$ K/W, $p_1 = 5$ W, $b = 4$ W, $c = 3.2$ W.

In figures 4 - 7 the calculated and measured dependences of the thermal resistance between the interior of the investigated transistor and the surrounding on the dissipated power (figures 4-6) or on the power supplied to the Peltier module (figure 7) at different cooling conditions of the considered transistor, are presented. In these figures points mark the results of measurements, while lines – the results of calculations obtained on the basis of the model proposed in this paper.

Figure 4 refers to the transistor operating without any heat-sink. In this case a dominant component of the thermal resistance of the transistor is the thermal resistance between the case and the surrounding R_{thc-a}. The increasing character of the dependence $R_{thc-a}(p_{th})$, which testifies the dominant role of the thermal conductivity in dissipation of the heat, determines the shape of the obtained curve. As it can be noticed, the range of changes of the value of the thermal resistance of the transistor is in the considered case not high and does not exceed 10%.
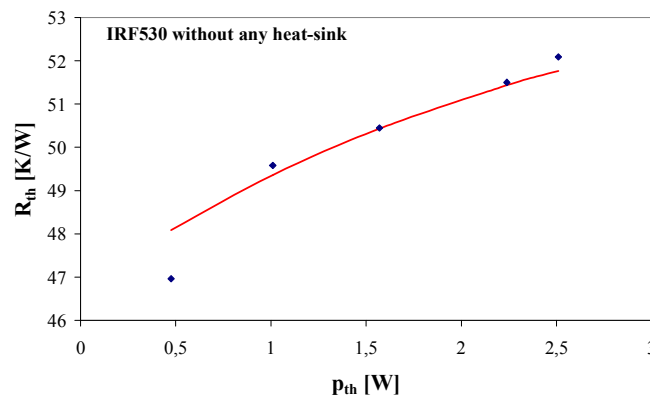

Figure 4. Calculated and measured dependences of thermal resistance of the IRF530 transistor operating without any heat-sink on the dissipated power.

In turn, figure 5 refers the transistor situated directly on the heat-sink. In comparison to the values obtained for the transistor without any heat-sink the almost tenfold fall in value of the thermal resistance of the investigated transistor is obtained. In the considered case, the thermal resistance between the case and the surrounding R_{thc-a} is omissible large in relation to the thermal resistance between the heat-sink and the surrounding R_{thr-a}. The decreasing character of the dependence $R_{th}(p_{th})$ shows that convection is a dominant mechanism of heat abstraction from the transistor.
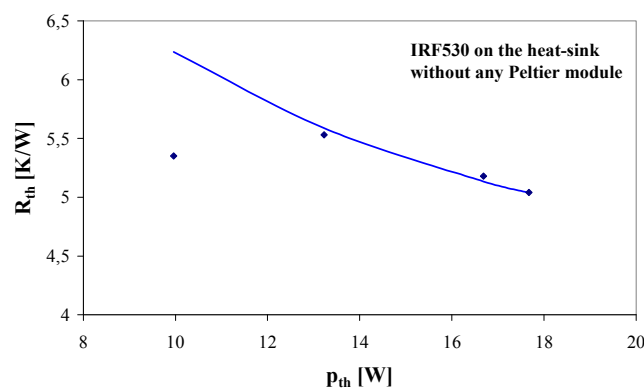

Figure 5. Calculated and measured dependences of thermal resistance of the IRF530 transistor situated on the heat-sink on the dissipated power.

In figure 4 the calculated and measured dependences of thermal resistance of the examined transistor on the power dissipated in the transistor at the zero-value of the power supplying the Peltier

module are compared, while in figure 5 the dependences of thermal resistance of this transistor on the power p_p are shown.

In both the considered cases the visible fall in the value of thermal resistance at an increase of the power dissipated in the transistor and the power supplying the Peltier module is obtained. It is worth noticing that the use of the not supplied Peltier module caused an increase over twice higher in the value of thermal resistance. It is the result of the introduction of the additional component of thermal resistance between the case of the device and the heat-sink. The forced cooling of the transistor by the use of the Peltier module allows decreasing the thermal resistance of the transistor even by about 20%, but it remain constant on the considerably higher level than in the case, when the Peltier module is not used.
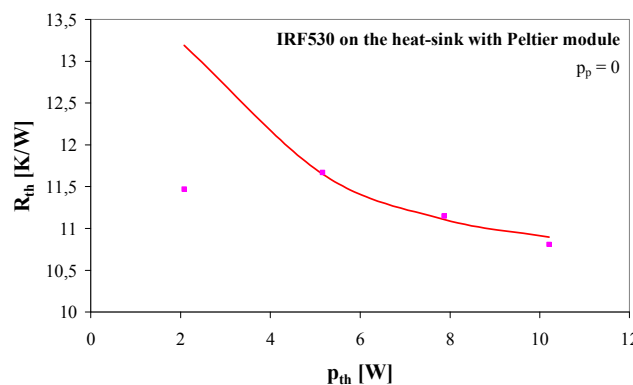

Figure 6. Measured and calculated dependence of thermal resistance of the transistor on the dissipated power.
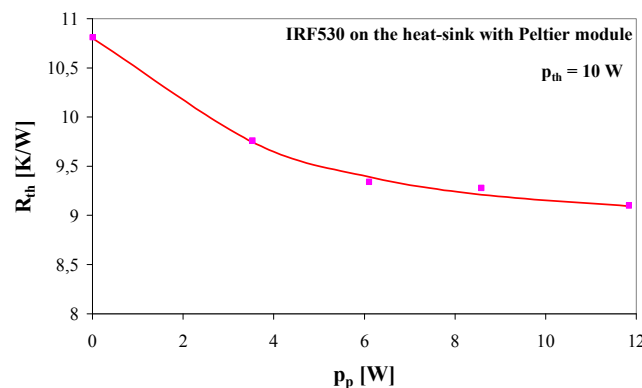

Figure 7. Measured and calculated dependence of thermal resistance of the transistor on the power supplying the Peltier module.

As it can be noticed, a satisfied agreement between the measured and calculated dependences $R_{th}(p_{th})$ and $R_{th}(p_p)$ is obtained in the range of high value of dissipated power. It testifies to the correctness of the proposed thermal model and the correctness of the estimation of the parameters values of this model.

5. Conclusions

In the paper the thermal model of power semiconductor devices taking into account the multipath and nonlinearity of the phenomena describing the heat transport is proposed. The detailed considerations are presented on the example of the power MOS transistor IRF530. The results of calculations and measurements shown in the paper prove the correctness of the proposed model. The parameters of this model are estimated on the basis of the catalogue data or from the simple measurement, which can be

performed by the user. The obtained results of the verification of the model both at free and forced cooling testify to the generality of the proposed model.

The proposed model describes thermal properties of investigated device at the steady state only. Currently the authors are conducting works the aim of which is to take into account in the presented model: thermal inertia, sizes and the shape of the heat-sink or printed circuit boards and the influence of the case of the device on efficiency of heat dissipation in the examined transistor.

6. References

[1]   Górecki K and Zarębski J 2013 Metodyka formułowania wielodrogowego nieliniowego skupionego modelu termicznego elementu półprzewodnikowego *Elektronika* **54 (**1) 22-25

[2]   Górecki K and Zarębski J 2012 Paths of the heat flow from semiconductor devices to surrounding *Proceedings of the 19th Internationa Conference Mixed Design of Integrated Circuits and Systems MIXDES* 313-318

[3]   Górecki K and Zarębski J 2010 Nonlinear compact thermal model of power semiconductor devices *IEEE Trans. on Components and Packaging Technologies* **33** (3) 643-647

[4]   D'Alessandro V and Rinaldi N 2002 A critical review of thermal models for electro-thermal simulation *Solid-State Electronics* **46 (**4) 487-496

[5]   Szekely V 1997 A new evaluation method of thermal transient measurement results *Microelectronic Journal* **28** (3) 277-292

[6]   Bagnoli PE, Casarosa C, Ciampi M and Dallago E 1998 Thermal resistance analysis by induced transient (TRAIT) method for power electronic devices thermal characterization *IEEE Trans. on Power Electronics, I. Fundamentals and Theory* **13** (6) 1208-19

[7]   Oettinger FF and Blackburn DL 1990 Semiconductor measurement technology: thermal resistance measurements *U. S. Department of Commerce* **NIST/SP-400/86**

[8]   Zarębski J and Górecki K 2007 A new measuring method of the thermal resistance of silicon p-n diodes *IEEE Trans. on Instrumentation and Measurement* **56** (6) 2788-2794

[9]   Zarębski J and Górecki K 2007 A new method for the measurement of the thermal resistance of the monolithic switched regulator LT1073 *IEEE Trans. on Instrumentation and Measurement* **56** (5) 2101-2104

[10]   Zarębski J and Górecki K 2007 A method of measuring the transient thermal impedance of monolithic bipolar switched regulators *IEEE Trans. on Components and Packaging Technologies* **30** (4) 627 – 631

[11]   Zarębski J and Górecki K 1995 A method of the BJT transient thermal impedance measurement with the double junction calibration *Proceedings of 11-th IEEE Semiconductor Thermal Measurement and Management Symposium (SEMI-THERM)* 80-82

[12]   Górecki K and Zarębski J 2009 Badanie wpływu wybranych czynników na parametry cieplne tranzystorów mocy MOS *Przegląd Elektrotechniczny* **85** (4) 159-164

[13]   Górecki K and Zarębski J 2013 Semiconductor component thermal model taking into account non-linearity and multhipathing of the cooling system *Proceedings of Microtherm 2013 Microtechnology and Thermal Problems in Electronics* 71-77

[14]   Zarębski J and Górecki K 2008 A method of the thermal resistance measurements of semiconductor devices with p-n junction *Measurement* **41** (3) 259-265

[15]   Prasher R 2006 Thermal interface materials: historical perspective, status, and future directions *Proceedings of the IEEE* **94** (8) 1571-1586

[16]   Padram M and Nazarian S 2006 Thermal modeling, analysis, and management in VLSI circuits: principles and methods *Proceedings of the IEEE* **94** (8) 1487-1501

[17]   Bar-Cohen A, Arik M and Ohadi M 2006 Direct liquid cooling of high flux micro and nano electronic components *Proceedings of the IEEE* **94** (8) 1549-1570

[18]   Sharp J, Bierschenk J and Lyon HB 2006 Overview of solid-state thermoelectric refrigerators and possible applications to on-chip thermal management *Proceedings of the IEEE* **94** (8) 1602-

1612

[19] Garimella SV, Singhal V and Liu D 2006 On-chip thermal management with microchannel heat sinks and integrated micropumps *Proceedings of the IEEE* **94** (8) 1534-1548

[20] Blackburn DL and Oettinger FF 1976 Transient thermal response measurements of power transistors *IEEE Trans. on Industrial Electronics and Control Instrumentation*, **IECI-22** (2) 134-141

[21] Zarębski J, Górecki K and Stepowicz WJ 1997 Wpływ sposobu zamocowania tranzystora na jego rezystancję termiczną *VI Konferencja Naukowa „Technologia Elektronowa" ELTE'97* **1** 708-712

[22] Górecki K, Zarębski J and Stepowicz WJ 2005 Wpływ wybranych czynników na parametry termiczne przyrządów półprzewodnikowych *Elektronika* **46** (10) 18-20

[23] 2002 IRF530 Data sheet *Fairchild Semiconductor* http://www.datasheetcatalog.org/datasheet/fairchild/IRF530.pdf

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