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Introduction

In this homework, characteristics of Diode and MOSFET will be investigated. Devices with different rating will be listed and compared. Their trade-off will be analyzed. Also term overdesign is going to be considered.

IMPORTANT DIODE PARAMETERS

1. V_F is the **forward voltage**. It refers to minimum voltage that diode needs to allow current flow
2. V_R is **reverse breakdown voltage**. It shows the maximum reverse voltage that the diode can hold. This parameter mostly depends on the doping and semiconductor characteristics. There is also another term called non repetitive peak reverse voltage V_{RSM}. It also refers to the maximum reverse voltage provided that it is not repetitive.
3. t_{rr} is the **reverse recovery time**. If a diode working in forward direction and suddenly changed to reverse direction it needs a time (t_{rr}) for becoming totally of. This is because free carriers inside the diode. (Electrons get back to n-side). In this time interval there exists a reverse current on diode.
4. t_{fr} is the **forward recovery time.** It is time required for diode to turn on when a forward voltage is applied. Same logic with reverse recovery time.
5. $I_{F(AV)}$ is the **average forward current**(maximum forward current). It shows the maximum amount of forward current allowed by diode. It is a repetitive value, that is, this amount of current does not harm diode for indefinite period.
6. T_j is the **maximum operating junction temperature**. This parameter refers to maximum operating temperature that diode can work without any deformation. This parameter is also related to total power dissipation.
7. I_R is the **reverse leakage current**. For an ideal diode, when a reverse voltage is applied to the diode it is not supposed to allow any current flow. However, for practical case there is a small amount of leakage current that flow through the diode when it is reverse biased. This current called reverse leakage current.
8. I_{RM} is the **reverse recovery current**. As it is stated in reverse recovery time, if condition of a diode changes from forward to reverse, for a small-time interval there is a reverse current flow due to carriers. This current is called reverse recovery current.
9. V_{fr} is the **forward recovery voltage**. When a forward bias is applied to the diode before it gets in steady state, forward voltage is first increase and then becomes its forward voltage. Forward recovery time refers to maximum voltage reached during this interval.
10. I_{FSM} is the **non-repetitive forward current.** Like I_F, it also shows the maximum forward current of the diode. However, while there is no time limitation in I_F(Diode can flow I_F for indefinite time period), in I_{FSM} there are time and magnitude limitation. That is diode can flow I_{FSM} for limited time interval without any deformation. Also, this amount of current should not flow through the diode repetitively.

Most important parameters are,

- Forward Current
- Reverse Voltage
- Forward Voltage
- Recovery Time
- Maximum junction temperature

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CURRENT RATINGS

1A Current Rating Diodes

Diode Types	Forward Voltage @If	Reverse Breakdown Voltage	Recovery Time	Reverse Current @Vr	Max Operating Temperature	Max Surge Current (Non Repetitive)
RGP10JE-E3/54	1.3V	600V	250ns	5uA	175 C	30A
1N4933GP-E3/54	1.2V	50V	200ns	5uA	175 C	30A
RS1004FL_R1_00001	1.3V	400V	150ns	1uA	150 C	30A
RGP10ME-E3/73	1.3V	1000V	500ns	5uA	175 C	30A

10A Current Rating Diodes

Diode Types	Forward Voltage @If	Reverse Breakdown Voltage	Recovery Time	Reverse Current @Vr	Max Operating Temperature	Max Surge Current (Non Repetitive)
PMEG045V100EPDZ	490mV	45V	17ns	50uA	175 C	210A
SBRT10U60D1-13	520mV	60V	20.8ns	400uA	150 C	140A
FFD10UP20S	1.15V	200V	<500ns	100uA	175 C	100A
S10ML-TP	1.2V	1000V	<500ns	10uA	150 C	200A
DMA10P1200UZ-TRL	1.55V	1200V	<500ns	5uA	175 C	110A

100A Current Rating Diodes

Diode Types	Forward Voltage @If	Reverse Breakdown Voltage	Recovery Time	Reverse Current @Vr	Max Operating Temperature	Max Surge Current (Non Repetitive)
VS-VSKE91/12	1.55V	1200V	>500ns	10uA	150 C	2020A
RHRU10050	2.1V	500V	60ns	500uA	175 C	1000A
VS-100BGQ100	1.04V	100V	<500ns	300uA	175 C	6300A
STTH200F04TV1	1.45V	400V	80ns	75uA	150 C	1000A

Figure 1: Same Current Rating Diodes Table

VOLTAGE RATINGS

5V Voltage Rating Diodes

Diode Types	Forward Voltage	Maximum Forward Current	Repetitive Reverse Voltage	Reverse Current @1V	Max Operating Temperature	Max Surge Current (Non Repetitive)
RB876WFHTL	350mV	10mA	5V	120uA	125 C	Not provided
RB886CMT2R	350mV	10mA	15V	120uA	125 C	Not provided
NSVR351SDSA3T1G	230mV	30mA	5V	25uA	125 C	-
RB160M-50TR	360mV	1A	50V	1.5mA	150 C	1A
MSG140	580mV	1A	40V	100uA	150 C	50A

50V Voltage Rating Diodes

Diode Types	Forward Voltage	Maximum Forward Current	Repetitive Reverse Voltage	Reverse Current @1V	Max Operating Temperature	Max Surge Current (Non Repetitive)
S1A-13-F	1.1V	1A	50V	5uA	150 C	30A
RB400VAM-50TR	550mV	500mA	50V	50uA	150 C	3A
S3AB-13-F	1.15V	3A	50V	10uA	150 C	100A
B550C-13-F	700mV	5A	20V	500uA	150 C	100A
SD101BW-E3-08	1V	15mA	50V	200nA	125 C	2A

500V Voltage Rating Diodes

Diode Types	Forward Voltage	Maximum Forward Current	Repetitive Reverse Voltage	Reverse Current @1V	Max Operating Temperature	Max Surge Current (Non Repetitive)
BYT79-500	1.38V	30A	400V	50uA	150 C	130A
1N5405-E3/54	1.2V	3A	500V	5uA	150 C	200A
BYC10DX-600	2.5V	10A	600V	200uA	150 C	65A
BYC20X-600	2.9V	20A	600V	200uA	150 C	250A

Figure 2: Same Voltage Rating Diodes Table

Part d) Looking at the diodes that have current rating of 1A, we see that if large reverse breakdown voltage is required, selected diode will probably have a large forward voltage. Therefore, in conduction mode power dissipation becomes larger. If we choose diode that has larger reverse breakdown voltage than we need (overdesign), power consumption increases. However, choosing larger reverse breakdown voltage might be helpful. For example, in the circuit if there is a large amount of reverse voltage on diode for a short time interval, our circuit may not be affected.

For 1N4933GP-E3/54 and RGP10ME-E3/73 having 50V and 1000V reverse breakdown voltage, respectively. While 1N4933GP-E3/54 has a forward voltage of 1.2V, RGP10ME-E3/73 has 1.2V. In addition, if we need high switching frequency but not large reverse breakdown voltage, choosing 1N4933GP-E3/54 is a better option. It is because recovery time of RGP10ME-E3/73 more than twice of recovery time of 1N4933GP-E3/54.

2- Referring to the diodes having voltage rating of 50V (S1A-13-F and B550C-13-F)
The diode S1A-13-F has maximum forward current of 1A and B550C-13-F has 5A. Furthermore, while S1A-13-F has reverse current of 5uA, B550C-13-F has 500uA. In this case, assuming that the maximum forward current is the only criteria, and it should be around 800mA. Choosing B550C-13-F is overdesign. This is because S1A-13-F has enough for our design. Even if B550C-13-F satisfies the requirement it has more leakage current. Also, since it has larger maximum forward current, it may be more expensive. It can differ a lot if millions of circuits are going to be produced.

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A) In this part of the homework, we were asked to define 10 most important mosfet parameters and choose the most important five of them. Actually depending of the application, important parameters could be changed.

1) V_{BRDSS} **(Breakdown Voltage):** Our first parameter is breakdown voltage for mosfet. Assuming that we have an enhancement mode mosfet (Most of the power mosfets are enhancement mode, depletion type is very rarely used in special applications like constant current sources for LED drivers) by shorting the gate and source terminals, we are ensuring that the mosfet is not conducting. Then by connecting a current source as in the figure below, we are measuring the voltage at 250uA current(typically, this current value could be changed).

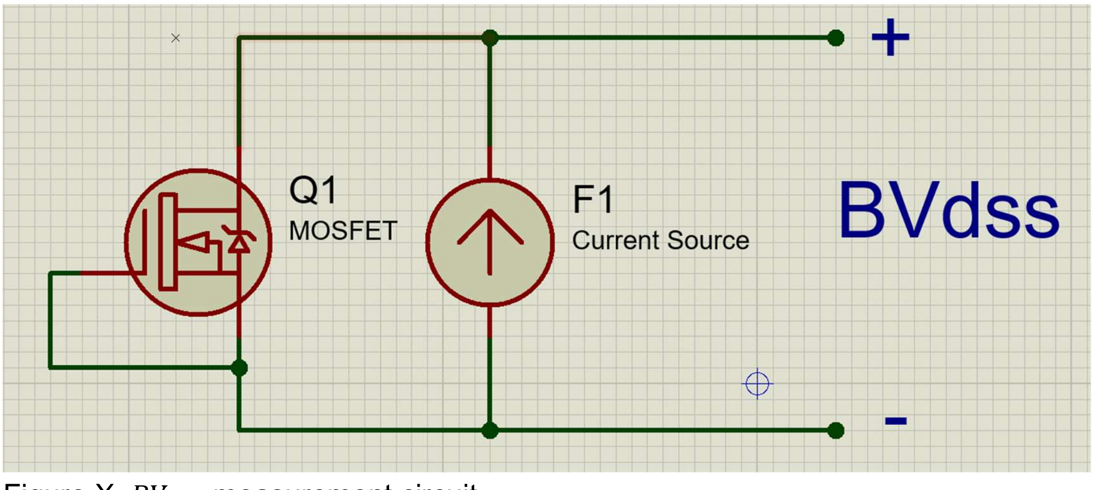

Figure X. BV_{DSS} measurement circuit

While designing a circuit, voltage between drain and source must not exceed that voltage. Moreover, due to inductances, voltage between drain and source could overshoot to higher than supply voltage, so we have to choose that value higher than our voltage and be careful at the layout stage.

2) $R_{DS(ON)}@V$ **On-resistance at voltage V:** This value is dependent on the voltage between gate and source, most of the companies share that value for 2 voltage: 4.5V and 10V. This is the resistance between drain and source at a given gate voltage. This value is also dependent on the temperature, so companies always share graphs for Vgs vs Rds and temperature vs Rds. This value is also used for conduction loss of mosfet. Circuit in the below figure is shown how to measure that value.

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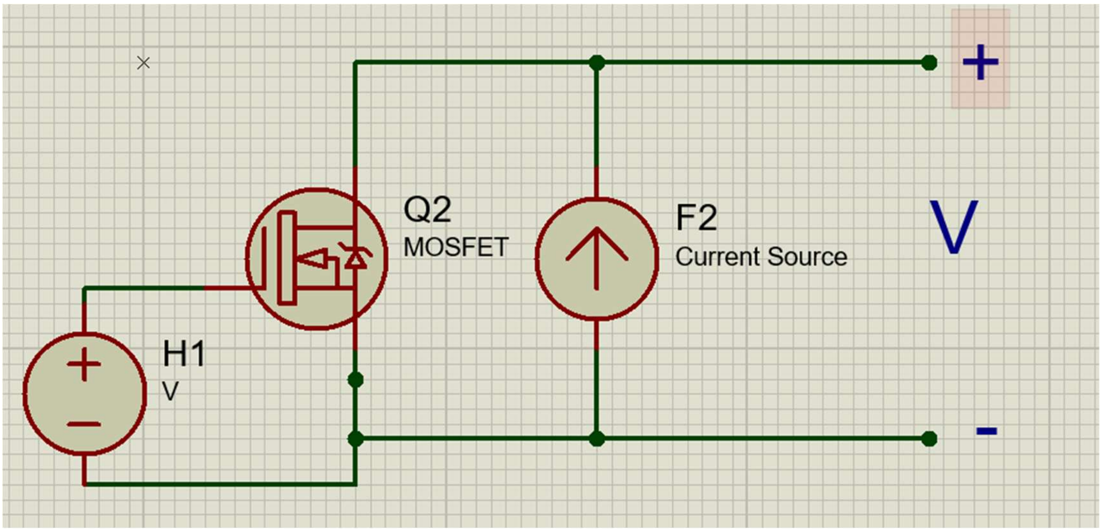

Figure X. Circuit for measuring Rds(on)

$$R_{DS(on)} = \frac{V}{value\ of\ current\ source}$$

3) $I_D@T$ **Continuous Drain current at temperature T:** This is the maximum continuous drain current of mosfet without damaging it. This value is not only dependent on temperature, but usually given with different temperature values, these temperature values could be case or junction. V_{GS} voltage as another parameter which affects this value since it is related with $R_{DS(ON)}$. Moreover, this value is not only about the design of the mosfet, since as a power electronics engineer we mostly do not design mosfets, we are buying semiconductors in certain packages like TO-220. This packages has standard sizes, and pinouts(some companies gives options of changing pinorder, but usually the pinouts of certain packages are standardized) and our mosfet(actually a piece of machined silicon wafer) is fitted inside of that package then connected to pins using wire bond machine and covered with a material. Due to the wire bond process and limitations of the standardized package, sometimes package limitation for current is lower than silicon limitation. This means that sometimes without changing the package, independent of the material of the semiconductor, we couldn't find the right semiconductor.

4) **Switching time parameters($t_{d(on)}$, $t_{d(off)}$, t_r, t_f):** These parameters are important for estimating switching loss of mosfet. We are defining 4 of them in the same category. They help us estimate the switching loss of mosfet, we cannot calculate it exactly since it depends on the load, driving circuit of the gate and other parameters.

Student 1: Mert Eren Kandilli & 2304855
Student 2: Goktug Tonay & 2305506

1) $t_{d(on)}$ *Turn-on delay time*: This time is defined as time interval between V_{GS} is reached 10% of driving voltage and V_{DS} is dropped to 90% of off time voltage.
2) $t_{d(off)}$ *Turn-off delay time:* This time is defined as interval between V_{DS} is reached of 10% of the off time voltage, and V_{GS} is dropped to 90% of driving voltage.
3) t_r *Rise time:* This time is considered as a major time of switching loss when turning-on of a mosfet. It is defined as V_{DS} is dropping to 90% to 10% of turn off time voltage.
4) t_f *Fall time:* Like in the rise time, this time is the major time of loss in turn off and it is defined as V_{DS} is rising from 10% to 90% of the voltage.

Switching loss is dependent on many parameters, but these values can be used the estimate the switching loss.(For example in half bridge configuration, due to dead time and body diode or parallel diode the switching loss can be assumed to be zero since the diode is in conduction while switching the mos.)

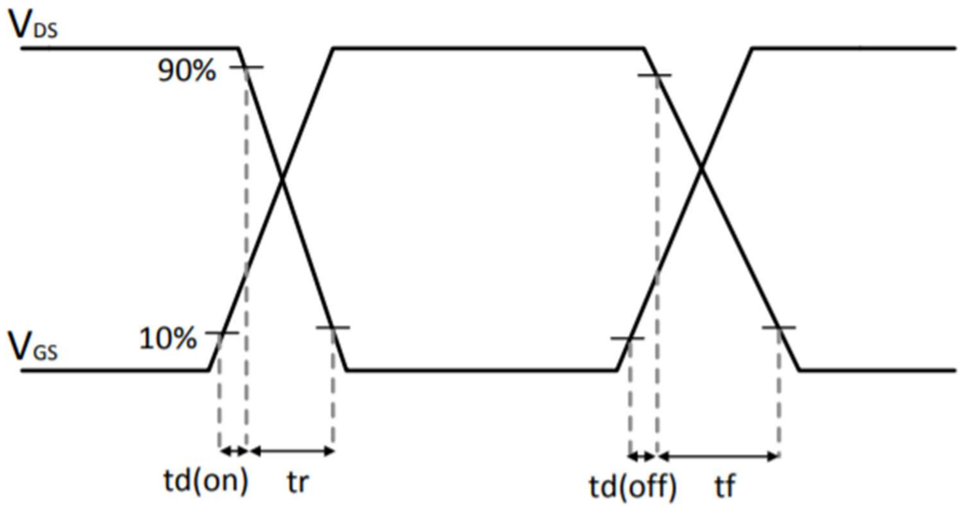

Figure X. Switching time in a graph from Taiwan semiconductors application note

These parameters were also achieved experimentally. Experiment circuit and parameters can be found in the datasheet of mosfet.

5) $V_{GS(th)}$ **Gate threshold voltage:** This voltage is defined as minimum required gate bias to form a conducting channel between source and drain. This voltage is measured by shorting drain and gate pins then again 250uA(this value can be changed) current source connected between drain and source. By measuring the gate to source voltage this value is obtained. This voltage has a negative temperature coefficient. This is the main reason behind the ic's negative temperature limit, below a certain temperature mosfet will start conducting unpredictably.(assuming that we are talking about enhancement

mode mosfets). Moreover, choosing that value lower causes false turn on in mosfets. We can give two example for them, first of it when we change the drain to source voltage in a short time(high dv/dt), due to capacitance between drain to gate and gate to source(forming a capacitive divider), gate driver could fail to keep mosfet in cutoff. Second of all, due to other switching operations, some voltage could induce at the gate-source capacitance. To sum up, choosing that value too low, could cause false turn-on and too high causes high losses.

6) $V_{GS(max)}$ **Maximum/minimum gate to source voltage:** This voltage is maximum and minimum gate to source voltage of a mosfet. Taking it for example ∓XV means that, gate to source voltage always should be in this region. Between gate-driver and mosfet legs paths create inductances and those inductances create overshoots, so the designer must be careful about layout. Also some mosfets like NVR4003N from ON semiconductor have embedded zener diodes to protect the gate.

7) $Q_g@V$ **Total Gate Charge at voltage V:** This is another parameter about the switching loss. Since the capacitance value of the capacitor in the gate-source terminal is dependent on the voltage, rather than talking about capacitance, talking about charge is more accurate. Some companies share both values in the datasheet. This charge must be supplied to the gate, to make gate-source voltage V. Higher gate charge means we need a more powerful gate driver to drive the gate. Selecting this value lower(assuming that gate driver circuitry stays the same) reduces the switching loss of the mosfet, since mosfet will reach the low Rds(on) state faster.

8) R_{th} **Thermal resistance from junction to case:** This value is defined as thermal resistance between junction and case. By using that value and approximate losses, we can calculate the operating temperature of our mosfet. However in most of the real life applications, we are connecting our mosfet to a heatsink, so we have more values to consider. We have to be sure that we are not exceeding the maximum junction temperature while working.

9) V_F **Body diode forward voltage:** Forward voltage of the body diode.

10) **Maximum Power Dissipation:** Most of the companies also share that value in the datasheet. This value means that somehow we managed to hold the case in 25 degree, losing that much power causes junction temperature rise

to max allowed temperature. This value can also be calculated but we should consider that thermal resistance is actually also a function of temperature difference(But since one of the temperatures is constant, in this particular example it is a function of temperature). I think it is beyond our scope(I think in this course we are only thinking of it as a switching device), but evaluating that value and safe operating curve of a mosfet is quite important for some of the applications.

Actually there are more important parameters, but we were asked to define 10 of them.

Again, by assuming that we are choosing a mosfet for switching applications(SMPS, motor drive etc.) I think most important parameters are: V_{BRDSS}, $I_D@T$, $R_{DS(ON)}@V$, $Q_g@V$, R_{th}.

B) In this part of the homework, we were asked to select mosfets with different current ratings.

1) I_D around 1A:
a) SSP1N60B from Fairchild Semiconductor
b) FDN363N from Fairchild Semiconductor
c) BSH105,215 from Nexperia USA Inc.
d) IRLM220ATF from onsemi
e) IXTH1N200P3 from IXYS

2) I_D around 10A:
a) IRLR120NTRPBF from Infineon Technologies
b) IRLZ14PBF from Vishay Siliconix
c) STL15N65M5 from STMicroelectronics
d) IRLS640A from onsemi
e) IRF740LCPBF from Vishay Siliconix

3) I_D around 100A:
a) SCT3022KLHRC11 from Rohm Semiconductor
b) PSMN4R0-30YLDX from Nexperia USA Inc.
c) FDL100N50F from onsemi
d) IAUC100N04S6L025ATMA1 from Infineon Technologies
e) IPP048N12N3GXKSA1 from Infineon Technologies

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Part Number	V_{BRDSS}	$I_D@T$	$R_{DS(ON)}@V$	$Q_g@V$ (V is same with $R_{DS(ON)}$)	R_{th}
SSP1N60B	600V	1A@Tc=25C	12Ω@10V	5.9nC	3.67C/W
FDN363N	100V	1A@Tc=25C	0.2Ω@10V	4nC	75C/W
IXTH1N200P3	2000V	1A@Tc=25C	40Ω@10V	23.5nC	1C/W
BSH105,215	20V	1.05A@Ta=25C	0.14Ω@4.5V	3.9nC	300K/W
IRLM220ATF	200V	1.13A@Ta=25C	0.8Ω@5V	10.3nC	62.5C/W
IRLR120NTRPBF	100V	10A@Tc=25C	0.185Ω@10V	20nC	3.1C/W
IRLZ14PBF	60V	10A@Tc=25C	0.2Ω@5V	8.4nC	3.5C/W
STL15N65M5	650V	10A@Tc=25C	0.335Ω@10V	22nC	2.4C/W
IRLS640A	200V	9.8A@Tc=25C	0.18Ω@5V	40nC	3.13C/W
IRF740LCPBF	400V	10A@Tc=25C	0.55Ω@10V	39nC	1C/W
SCT3022KLHRC11	1200V	95A@Tc=25C	22mΩ@18V	178nC	0.27C/W
PSMN4R0-30YLDX	30V	95A@Tc=25C	3.4mΩ@10V	9.1nC	2.14K/W
FDL100N50F	500V	100A@Tc=25C	43mΩ@10V	238nC	0.05C/W
IAUC100N04S6L025ATMA1	40V	100A@Tc=25C	2.06mΩ@10V	25nC	2.4K/W
IPP048N12N3GXKSA1	120V	100A@Tc=25C	4.1mΩ@10V	137nC	0.5K/W

By looking at the table above we can make some comments. The very basic one is, while reducing the Rds(on) value, Qg value rises. That means that if we choose a low Rds(on) mosfet to lower the conduction losses, this choice will cause higher switching losses. While preparing the table, we ignored the packaging of mosfets, so actually making a comparison is not true. But we can also see from the table, in the same current rating, Rds(on) values are not much different from each other (2 exceptions from 1A case) and while the breakdown voltage rises, the gate charge also rises.

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C) In this part of the homework, we were asked to select mosfets with different breakdown voltage ratings.

1) V_{BRDSS} **around 5V:**
   a) PI5101-01-LGIZ from Vicor Corporation
   b) SIA414DJ-T1-GE3 from Vishay Siliconix
   c) AON2400 from Alpha & Omega Semiconductor Inc.
   d) SI1450DH-T1-GE3 from Vishay Siliconix

2) V_{BRDSS} **around 50V:**
   a) RU1J002YNTCL from Rohm Semiconductor
   b) IRLR2705TRPBF from Infineon Technologies
   c) IRL3705ZSTRLPBF from Infineon Technologies
   d) IRF3805STRL-7PP from Infineon Technologies

3) V_{BRDSS} **around 500V:**
   a) LND150K1-G from Microchip Technology
   b) IRFR420ATRPBF from Vishay Siliconix
   c) FDPF20N50FT from onsemi
   d) IXTA6N50D2 from IXYS
   e) STY105NM50N from STMicroelectronics

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Part Number	V_{BRDSS}	$I_D@T$	$R_{DS(ON)}@V$	$Q_g@V$ (V is same with $R_{DS(ON)}$)	R_{th}
PI5101-01-LGIZ	5V	60A@Ta=25C	360uΩ@4.5V	65nC	-
SIA414DJ-T1-GE3	8V	12A@Tc=25C	9mΩ@4.5V	21nC	5.3C/W
AON2400	8V	8A@Ta=25C	11mΩ@2.5V	16nC	-
SI1450DH-T1-GE3	8V	6.04A@Ta=25C	39mΩ@4.5V	4.7nC	34C/W
RU1J002YNTCL	50V	0.2A@Ta=25C	1.6Ω@4.5V	-	-
IRLR2705TRPBF	55V	28A@Tc=25C	40mΩ@10V	25nC	2.2C/W
IRL3705ZSTRLPBF	55V	75A@Tc=25C	6.5mΩ@10V	40nC	1.14C/W
IRF3805STRL-7PP	55V	160A@Tc=25C	2mΩ@10V	130nC	0.5C/W
LND150K1-G	500V	13mA@Tj=25C	1KΩ@0V	-	-
IRFR420ATRPBF	500V	3.3A@Tc=25C	3Ω@10V	17nC	1.5C/W
FDPF20N50FT	500V	20A@Tc=25C	0.22Ω@10V	50nC	3.3C/W
IXTA6N50D2	500V	6A@Tc=25C	0.5Ω@0V	96nC@ 5V	0.41C/W
STY105NM50N	500V	110A@Tc=25C	19mΩ@10V	326nC	0.2C/W

Again the most basic comment on the table, in the same voltage rating while current rating is rising, the Rds(on) value is dropping. Moreover, we can actually say that Rds(on) value and Qg are inversely proportional.

Ç) Main trade-off while selecting a mosfet is between conduction loss and switching loss. To lower conduction loss, we need to find a mosfet with low Rds(on), but low Rds(on) usually introduce higher Qg, this means that our switching loss is increased. But actually this is not all, we can select a higher voltage mosfet than normal conditions(bad layout could be cause this) this will cause us higher loss in total. But assuming that we are good engineers, and selecting appropriate Vds breaking voltage and Id current, our trade off will be between Qg and Rds(on).

Choosing an over design mosfet will cost us more. But will give us a major advantage of making mistakes. We should be careful about selecting semiconductors,choosing an overdesigned one will cost more or lose more.

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Conclusion

In this homework, we studied diodes and mosfets. We firstly investigate important parameters of them. We defined those parameters and selected the most important 5 of them for selecting a device. Those 5 parameters are very helpful in designing a circuit. By looking at those parameters we can basically calculate the conduction and switching losses of a diode or mosfet, we can learn the suitable voltage and current values for them. Then we selected diodes of different voltage and current ratings. With those selections, we learn the trade-offs of the real world. For example, if we select the blocking diode of voltage more than needed then we will face more losses in our circuit. Moreover, we also selected mosfets of different voltage and current values also. These selections taught us the disadvantages of overdesigning a circuit. By selecting overdesign components, we are facing higher costs and/or losses in our circuits. Because of that, we have to be careful about selecting semiconductor devices.

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7)