Class D Amplifier - Device Test

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Summary

This report discusses the operation of a class D amplifier used to test two MOSFET switching devices.

1 Theory of Operation

1.1 Safety Protocol

When using an oscilloscope, the operator must be sure that she is not creating a sneak path. When soldering, one must use safe soldering practices. Safe practices include, keeping the sponge wet, wearing safety glasses at all times, properly tinning the soldering iron, and unplugging the soldering station when finished.

1.2 Circuit Operation

Device	Function
U1	DC-DC Isolated Converter - LCOM
U2	DC-DC Isolated Converter - UCOM
U3	Linear Dropout Regulator
U4	Single Inverting Buffer Driver
U5	Digital Isolator - UCOM
U6	MOSFET Gate Driver - UCOM
U7	Single Inverting Buffer Driver
U8	Digital Isolator - LCOM
U9	MOSFET Gate Driver - LCOM

1.3 Double Pulse Test

The double pulse test is designed to test the switching characteristics of the device that is being tested. The double pulse test has 4 parts t1,t2,t3, and t4, the first pulse generated during t1 is the initial turn on of the circuit. The second pulse generated during t2 is the initial turn off of the circuit. These two test the initial switching characteristics of the device, but the second pulse is necessary to test the diode recovery of the device. In this experiment, the device being tested is an Infineon 0IPD60R38C6 MOSFET.

1.4 Energy Loss

Based on the theoretical analysis seen in the calculations section It has been determined that,

$$E_on = 500nJ\ E,on = 2.38\mu J$$

The experimental results indicate the following

$$E,on = 1.312\mu J\ E,on = 5.496\mu J$$

The experimental results yield losses nearly twice what was calculated in theory based on the datasheet. The differences in these values could be due to many factors at play. In order to calculate the theoretical losses, the typical values were used from the data sheet. There could be a high range of potential loss values depending on the switches environment, but it would be difficult to determine because there are no minimum or maximum values in the datasheet. The energy losses that occur in the simulated circuit are discussed below in the simulation section.

2 Calculations

2.1 Double Pulse Test

The double pulse test should generate a pulse signal so that the current across the inductor to have a maximum current of 2A. In order to insure that the current a maximum current, the first pulse must be of the proper length in time. The length, in time, of the second pulse does not need to be taken into consideration due to fact that the off time between the first and second pulse should have the same length as the second pulse (both are $10\mu s$). In order to determine how long the first pulse should be, one could manipulate the following relationship to determine the change in current across the inductor with respect to time.

$$V_L = L * di/dt \tag{1}$$

$$\Delta i/\Delta t = V_L/L \tag{2}$$

$$\Delta t = L\Delta i/V_L \tag{3}$$

Due to the nature of the circuit, it is apparent that the initial current across the inductor will be $0A$. Therefore, $\Delta i/\Delta t$ will be equal to the maximum current of the inductor, and from this relationship, we can isolate the time step of the pulse, Δt. The input voltage to the circuit is $20V$, and the inductance of the load is $370\mu H$. Using these values, we yield the following result.

$$\Delta t = \frac{(370\mu H)(2A)}{(20V)} = 37\mu s \tag{4}$$

Because it is required that entire length of the pulse test is 1s. The first on pulse should last $37\mu s$, the first off cycle should last $10\mu s$, the second pulse cycle should last $10\mu s$, and the fourth off cycle should be $999943\mu s$.

2.2 Switching Losses

Using the values in the datasheet, calculate the approximate values for the energy loss during turn-on and turn-off of the power MOSFETs. The energy loss for the turn-on time and the turn-off time can be approximated as Equation 5 and Equation 6, respectively.

$$E_{ON} = \frac{1}{2} V_{DS} I_D (t_{ON} + t_r) \tag{5}$$

$$E_{OFF} = \frac{1}{2} V_{DS} I_D (t_{OFF} + t_f) \tag{6}$$

Due to the nature of the circuit we can deduce the following.

$$V_{DS} = V_{IN} = 20V$$
$$I_D = I_L = 2A$$

According to the datasheet for the MosFets in the circuit, Inferion IPx60R380C6, we know the following characteristics of the component.

$$t_{ON} = 15ns \; t_r = 10ns$$
$$t_{OFF} = 110ns \; t_f = 9ns$$

Using the above information, the E_{ON} and E_{OFF} can be determined using Equation 1 and Equation 2.

$$E_{ON} = \tfrac{1}{2}(20V)(2A)(15ns + 10ns) = 500nJ$$
$$E_{ON} = \tfrac{1}{2}(20V)(2A)(110ns + 9ns) = 2.38\mu J$$

Using data generated from the experiment, the turn on and turn off energies were calculated. The following figures are generated from a MatLab script located in Appendix 1. The following equation is used to calculate the turn on and turn off energy.

$$E_{ON} = \tfrac{1}{2}\Sigma V_{DS} * I_D * t_{ON}$$
$$E_{OFF} = \tfrac{1}{2}\Sigma V_{DS} * I_D * t_{OFF}$$

The code multiplies the drain current and the drain to source voltage together to obtain the instantaneous power of each sample, sums up the instantaneous power at each sample during the rise time and the fall time to obtain the total power loss for each, then multiplies the rise time and fall time intervals by their power losses respectively to obtain the rise time energy and the fall time energy.

In analyzing the waveforms, I noticed that the apparent t_{ON} and t_{OFF} appear to be significantly different than the typical values listed in the Inferion IPx60R380C6 datasheet. I used the cursor tool in MatLab to determine the functional values of the total turn on and total turn off time. In the computational analysis, I use $t_{ON,tot} = 44ns$ and $t_{OFF,tot} = 50ns$.

The computations executed in MatLab yield the following values for the switching energy.

$$E_{ON} = 1.312nJ$$
$$E_{OFF} = 5.496\mu J$$

The experimental values results appear to show roughly twice the switching energy than the experimental calculation.

The following two figures depict the graphs of the rise time and fall time for the double pulse test.

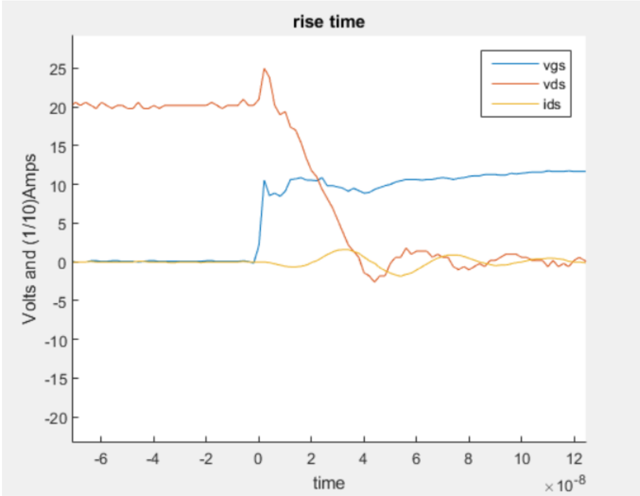

Figure 1

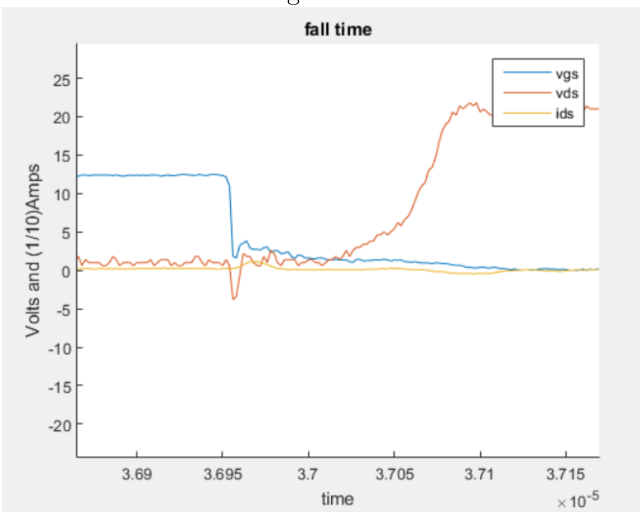

Figure 2

2.3 Heat Losses

It is given that the the ambient temperature T_A is 30^oC and T_J must be below 65^oC. It is also given that the switching frequency, f_S, is $50kHz$. The power loss on the MOSFET can be calculated in Equation 7 Below.

$$P_{Q,Loss,Tot} = (E_{ON} + E_{OFF}) * f_S \tag{7}$$

$$P_{Q,Loss,Tot} = (500nJ + 2.38\mu J) * 50kHz = 144mW$$

According to the datasheet the thermal resistance from the junction to the case,$R_{\theta,JC}$, $65^oC/W$. In the following calculations it is assumed that the thermals resistance from the case to the source ,$R_{\theta,CS}$, is $1^oC/W$. The relationship between the thermal resistance of the heat sink, $R_{\theta,SA}$, and the maximum junction temperature, T_J, is defined by Equation 8.

$$R_{\theta,SA} = \frac{T_J - T_A}{P_{Q,Tot}} - R_{\theta,JC} - R_{\theta,CS} \quad (8)$$

$$R_{\theta,SA} = \frac{65^oC - 30^oC}{144mW} - 1.5^oC/W - 1^oC/W$$

$$R_{\theta,SA} = 240.5^oC/W$$

It is important to be sure that this experiment uses an inductor that does not saturate at the desired current for this experiment. According to the datasheet for the N87 ferrite core, the effective magnetic path length, l_e, is $120.4mm$, the effective cross sectional area, A_e, is $195.7mm^2$, the magnetic saturation, B_sat, is $490mT$, and the the relative permittivity, μ_e, is 2200. The permittivity of air is assumed to be equal to the permittivity in a vacuum, $4 * \pi * 10^{-7}$. In order to calculate the saturation current of an inductor, the number of turns required to create the conductor using the given ferrite core must be calculated. The relationship between turns and inductance is illustrated below in Equation 9 where R is the magnetic reluctance.

$$L = \frac{N^2}{\rho} \quad (9)$$

The magnetic reluctance, R, can be calculated using Equation 10 below.

$$R = \frac{l_e}{\mu_r \mu_\sigma A_e} \quad (10)$$

$$R = \frac{120.4mm}{(2200)(4*\pi*10-7)(195.7mm^2)} = 223336.3\frac{AN}{Wb}$$

Now that we have the reluctance, we can use equation 10 to solve for the turns ratio.

$$N = \sqrt{LR} = \sqrt{(150\mu H)(223336.3)} = 5.78- > 6Turns$$

The relationship between the saturation current and the ferrite core characteristics is determined by Equation 11 below.

$$i_{sat} = \frac{B_{sat} l_e}{N \mu_r \mu_\sigma} \quad (11)$$

$$i_{sat} = \frac{(490mT)(120.4mm)}{(6turns)(2200)(4 * \pi * 10-7)} \quad (12)$$

The double pulse test is designed so that the maximum current through the inductor is 2A. Because the inductor has a saturation current of 3.56A, it should not saturate during this experiment.

However, the experimental results show that the inductor does in fact saturate. The figure below depicts the inductor current waveform in purple.

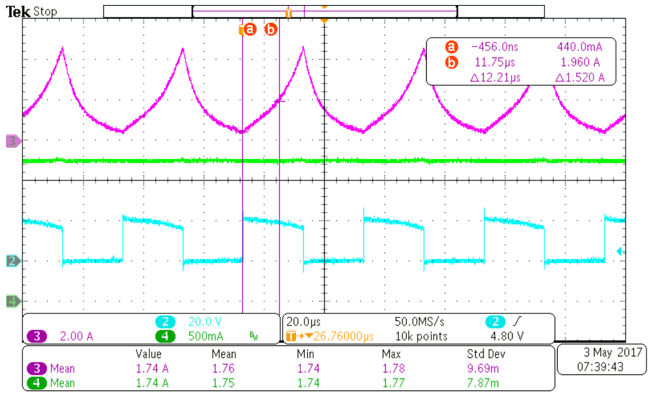

Figure 3

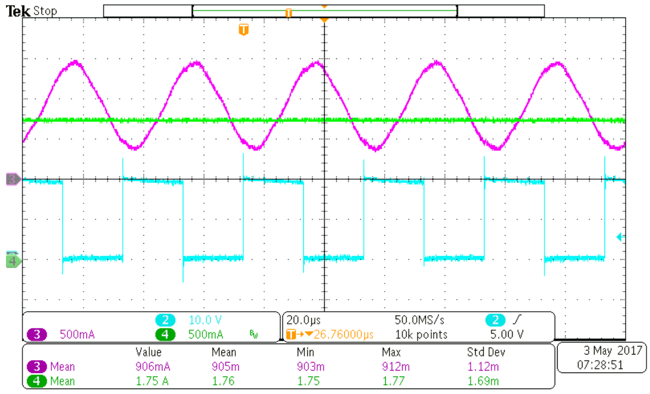

Figure 4

The cursors in the image mark the boundary at which the inductor begins to saturate. If we use these to determine the slope of the inductor current, we can then find the peak to peak current of the inductor. The slope of the current can be calculated using the following equation.

$$\frac{\Delta A}{\Delta \mu s} = \frac{1.520A}{12.21\mu s} = 0.124\frac{A}{\mu s} \quad (13)$$

The period is 40s, and the duty cycle is 0.5, so the charge time of the inductor should be 20s. This means that the experimental peak to peak inductor current is 0.124A/us*20us = 2.48A. In a buck converter the average inductor current is equal to the average output current. The output current is displayed in Figure 4 above as the green waveform. Usually, there is ripple in the output voltage, but due to the large value of capacitor in parallel with the output current, it appears to have no ripple. This makes it easy to determine the average output current and average inductor current which are both 1.75A. The peak inductor current can be determined by the following equation.

$$i_{l_peak} = i_{l_avg} + \frac{1}{2} i_{l_pp} \quad (14)$$

$$i_{l_peak} = 1.75A + \tfrac{1}{2}(2.48) = 2.99A$$

As calculated using equation 8, the theoretical saturation current of the inductor should be 3.56A. Because the peak inductor current does not reach this value, the inductor should not have saturated.

The theoretical efficiency of a buck converter, or any converter for that matter, is 1. Meaning that the input power and output power are the same. Efficiency is calculated according to Equation 15 below.

$$\nu = \frac{P_{out}}{P_{in}} \tag{15}$$

$$V_{in} = 19.77V \; V_{out} = 8.66V \; I_{in} = 0.905A$$
$$I_{out} = 1.75A$$

Using Equation 15 and the values above, we can determine the experimental efficiency of the buck converter.

$$\nu = \frac{(8.66V)(1.75A)}{(19.77V)(0.905A)} = 0.847$$

3 Simulation Results

The following two images depict the schematic and the simulation results of the double pulse test, respectively. In the schematic, a three state MOSFET is used to represent Q1. A three state MOSFET is needed in order to simulate the parasitic properties of the device which cause stray inductance. As seen in the schematic below, there is a capacitor between each the gate and the source, the drain and the source, and the gate and the drain. Each capacitor represents the parasitic capacitance between each of the pins, due to the nature of the distance and material between them. The parasitic capacitance between the pins on the MOSFET is determined by the following relationships.

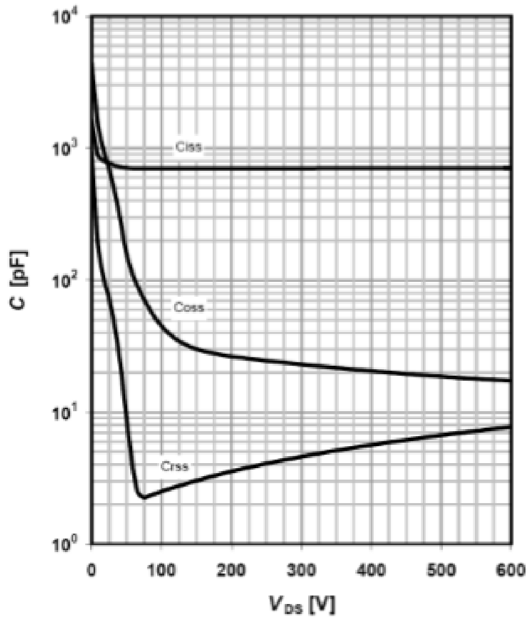

Figure 5

$$C_{OSS} = C_{GD} + C_{DS} \tag{16}$$

$$C_{ISS} = C_{GD} + C_{GS} \tag{17}$$

$$C_{RSS} = C_{GD} \tag{18}$$

C_{OSS}, C_{ISS}, and C_{RSS} are found in the IPD60R380C6 datasheet. $C_{OSS} = 800pF$, $C_{ISS} = 800pF$. In the double pulse test simulation, it is also clear based on the graph that $C_{RSS} = 200pF$. With this information, it is determined that $C_{GD} = 200pF$, $C_{GS} = 600pF$, and $C_{DS} = 600pF$. In addition to the parasitic capacitance, this simulation also accounts for stray inductance. In order to model this phenomenon in pSim, a 100μH inductor is added in series between the load inductor (370μ H) and the drain of the MOSFET.

The double pulse simulation results appear in Figure 6, it is clear that as vgs turns off, and the MOSFET begins to block, V_{DS} has a strong overshoot when rising, and there is some ringing as V_{DS} is equal to V_{in}

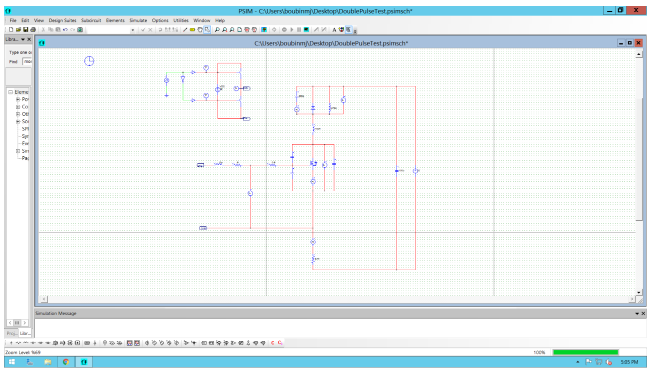

Figure 6

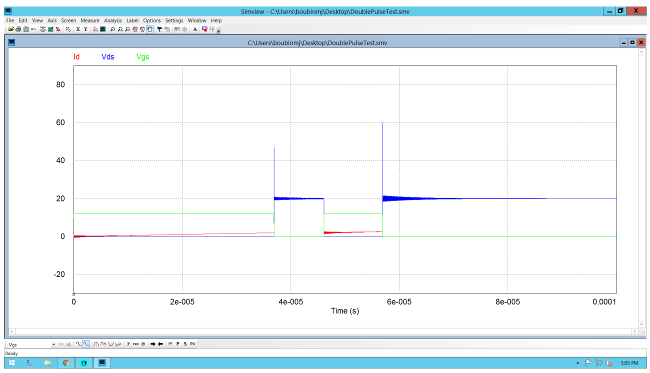

Figure 7

In order to reduce the ringing in the simulation, one can add elements into the circuit designed mitigate any parasitic capacitance or stray inductance that is occurring. However, if all of the parasitic elements of the circuit are removed from the simulation, the waveforms will not show any ringing. This is equivalent to simulating a circuit with infinite distance between each of the MOSFETs pins or putting a material with infinite resistance between the MOSFETs pins. In practice, this is not realistic, but it will allow us to clearly demonstrate what the waveforms, particularly V_{DS} will look like when there is no ringing. As you can see in Figure 9, there is no overshoot or ringing in any of the signals.

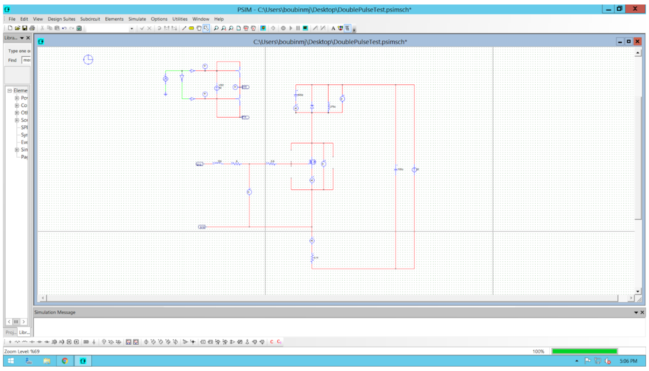

Figure 8

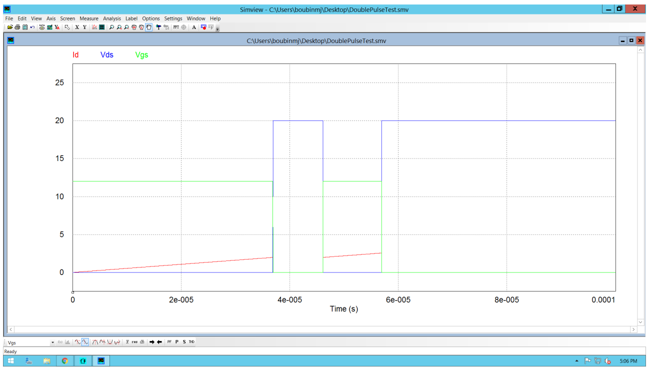

Figure 9

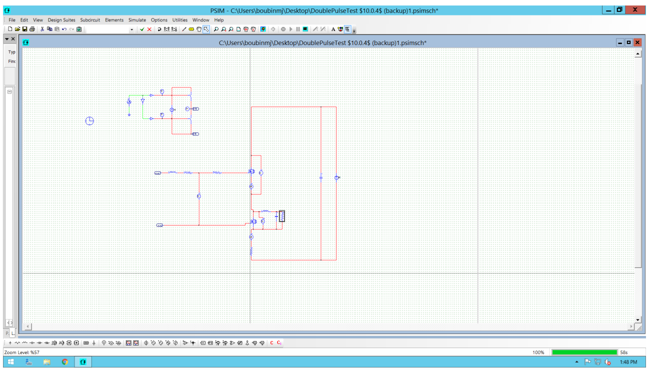

Figure 10

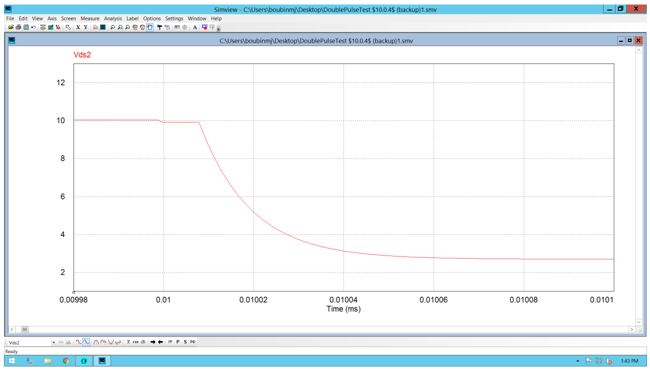

Figure 11

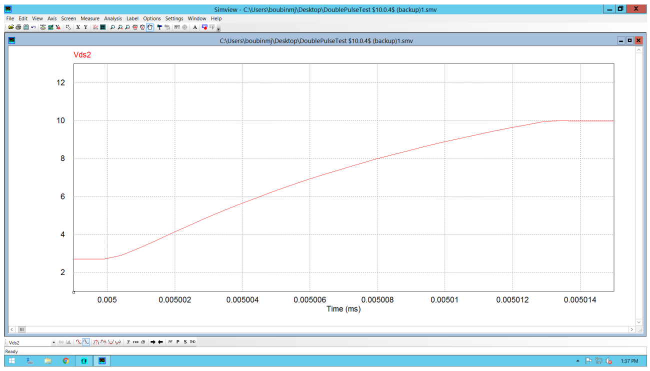

Figure 12

Figure 10 above depicts the schematic used for the buck converter. Figures 11 and 12 show the rise time and fall time of the switch voltage (Vds). According to the images the on time seems to be 80ns and the off time appears to be 12ns. Also there does not appear to be delay. These times are relatively close to the values that appear in the datasheet, but yield slightly lower switching energies than the calculated values.

4 Conclusion

I was able to created a PCB board, assemble it with the proper components, and test the MOSFETs (Infineon IPD60R380C6) successfully with results that were close to what I expected in a double pulse test and a buck converter test. My board also was able to withstand a 400V double pulse test.

5 References

[1] Infineon Technologies Infineon IPx60R380C6. Munchen, Germany 2015

[2] Kotak V.C. DC to DC converter in Maximum Power Point Tracker. Mumbai, India. IEEE, 2013

[3] Tian, Bozhi. Coaxial Silicon Nanowires as solar cells and nonoelectronic power sources. Nature Publishing Group, 2007

[4] Qu, Ronghai Influences of Generator Parameters on Fault Current and Torque in a Large Scale

Superconducting Wind Generator. IEEE. 2015

6 Appendix I

load('TEK0003ALL');

figure hold on; plot(time, CH2); plot(time, CH3); plot(time, CH4); hold off; title('rise time') xlabel('time') ylabel('Volts and (1/10)Amps') legend('vgs', 'vds', 'ids')

figure hold on; plot(time, CH4); hold off; title('current')

$findex_begin = find(time == 3.7e - 5, 1)$; $findex_end = find(time == 3.705e - 5, 1)$;

pFall = 0;

$fori = findex_begin : findex_end\ pFall = pFall + CH3(i) * 10 * CH4(i)$; end

$eFall = pFall * (time(findex_end) - time(findex_begin))$;

$rindex_begin = find(time == 0, 1)$; $rindex_end = find(time == 4.4e - 08, 1)$;

pRise = 0;

$forj = rindex_begin : rindex_end\ pRise = pRise + CH4(i) * CH3(i)$; end

$eRise = pRise * (time(rindex_end) - time(rindex_begin))$;