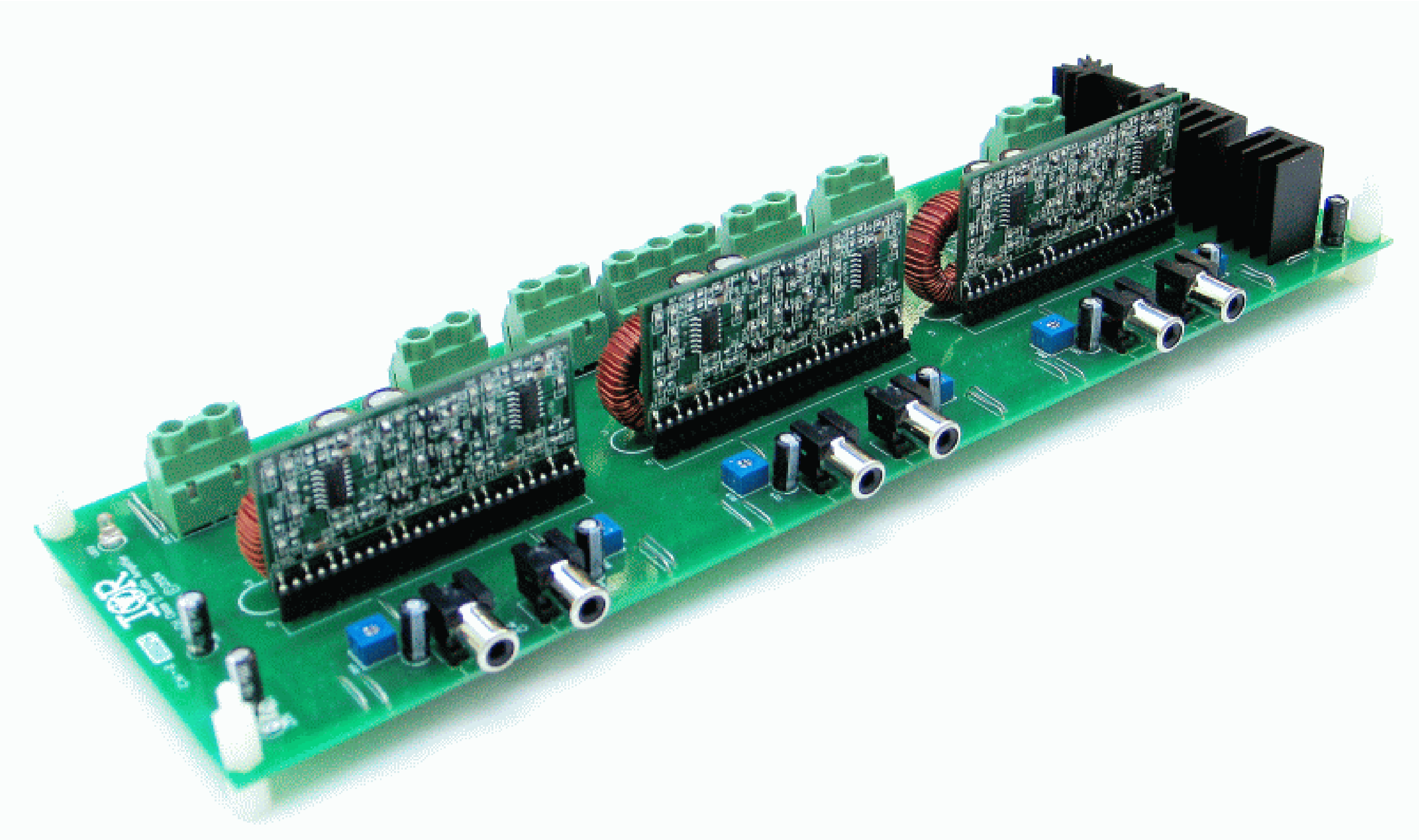
Designing Practical High Performance Class D Audio Amplifier



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Chapter 1 • **Class D Amplifier Introduction**

Theory of class D operation, Points of design

Chapter 2 • **The latest Digital Audio MOSFET, DirectFET® MOSFET**

Importance of layout and packaging

Optimized MOSFET for no-heat sinking

Chapter 3 • **Designing Dead-time and Overload Protection with Digital Audio Gate Driver IC**

Designing with built-in dead-time generation

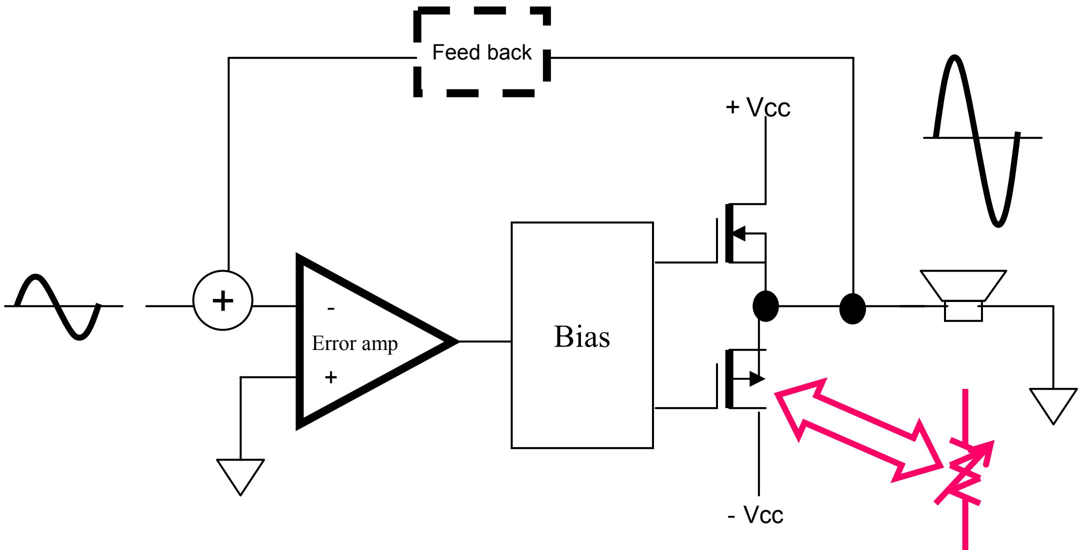
How to design OCP. Tj estimation.

Chapter 4 • **Design Example**

No-heat sink 100W x 6ch compact Class D amplifier

Chapter 1 Class D Audio Overview

Review: Traditional Class AB Amplifier



η = 30% at temp rise test condition.

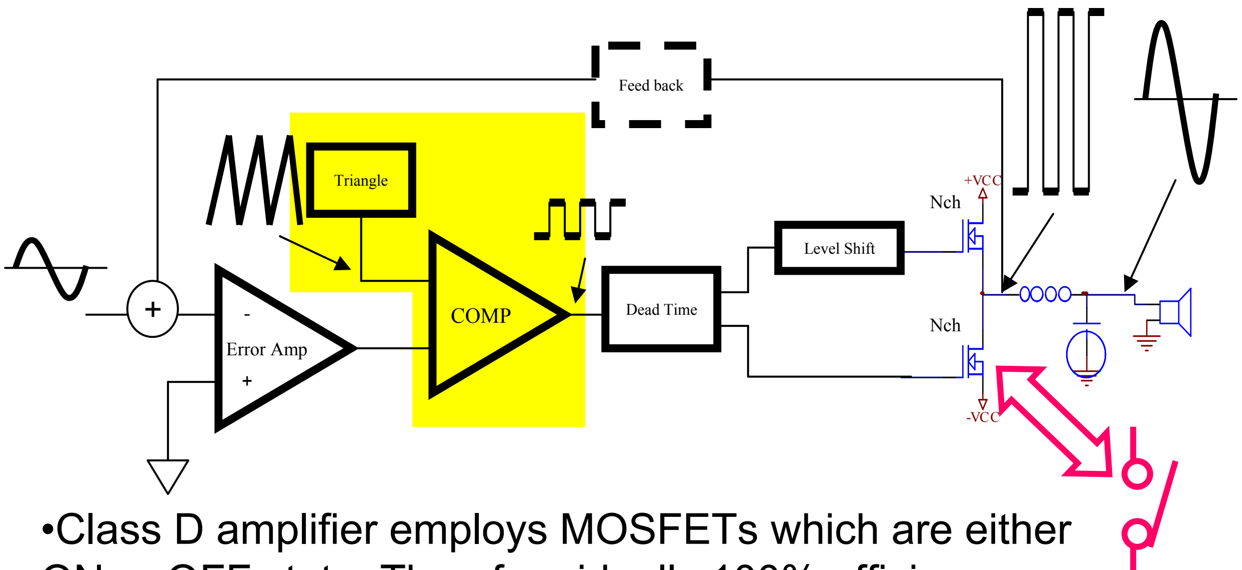
- Class AB amplifier uses linear regulating transistors to modulate output voltage.

- A loss in the regulating transistor in Class AB amplifier is proportional to the product of the voltage across the device and the current flowing through it.

$$P_C = V_{CE} \cdot I_C$$

➔ Independent of device parameter

Class D Amplifier



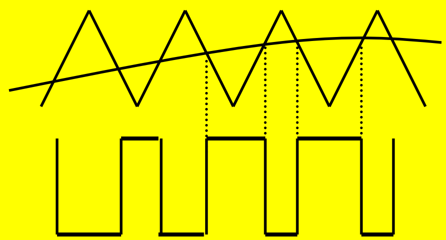
- Class D amplifier employs MOSFETs which are either ON or OFF state. Therefore ideally 100% efficiency can be achieved.

- PWM technique is used to express analog audio signals with ON or OFF states in output devices.

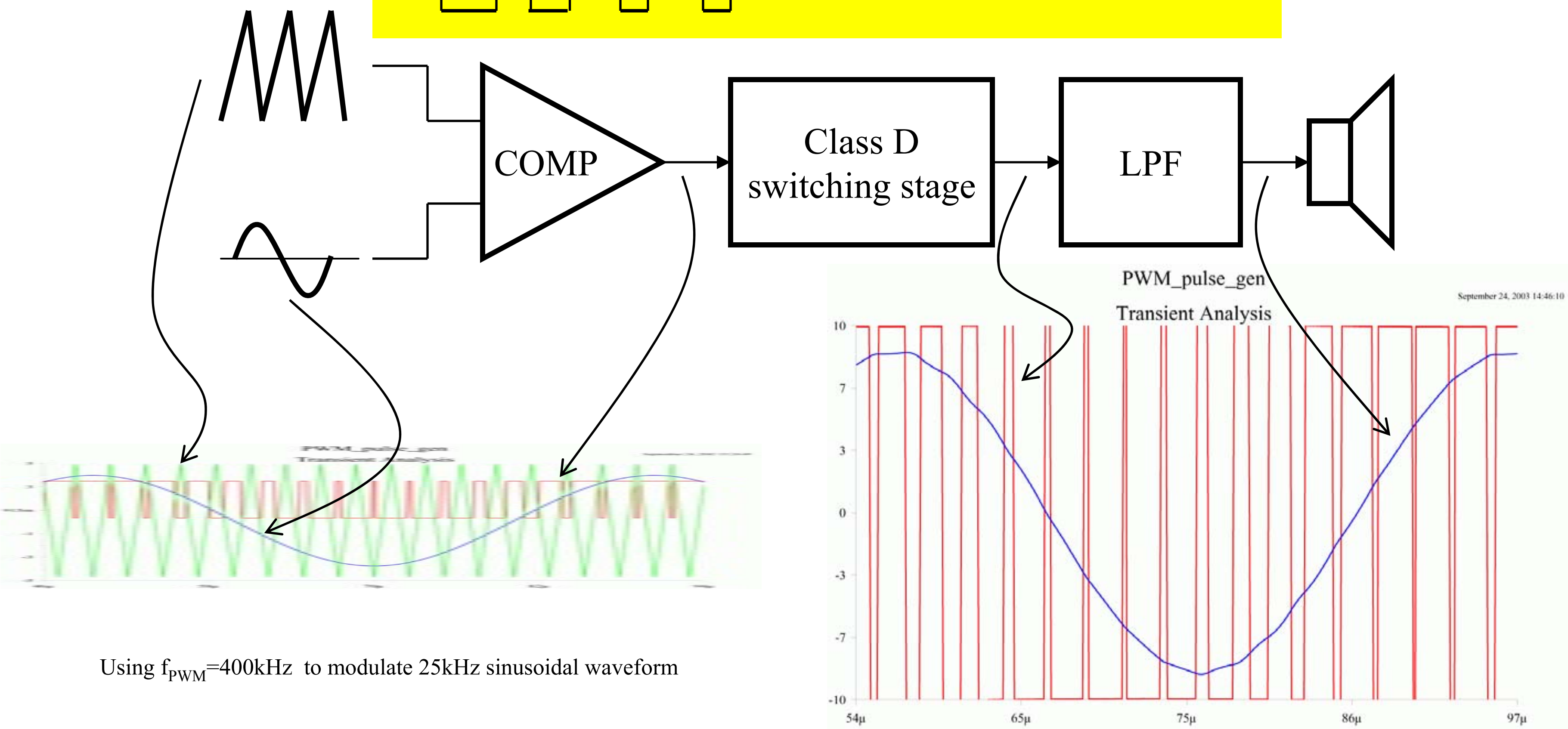
- A loss in the switching device caused by 1)finite transition speed, 2)ON state resistance and 3)gate charge. $P_{TOTAL} = Psw + Pcond + Pgd$

➔ dependent of device parameter ➔ can be improved further!

Basic PWM Operation

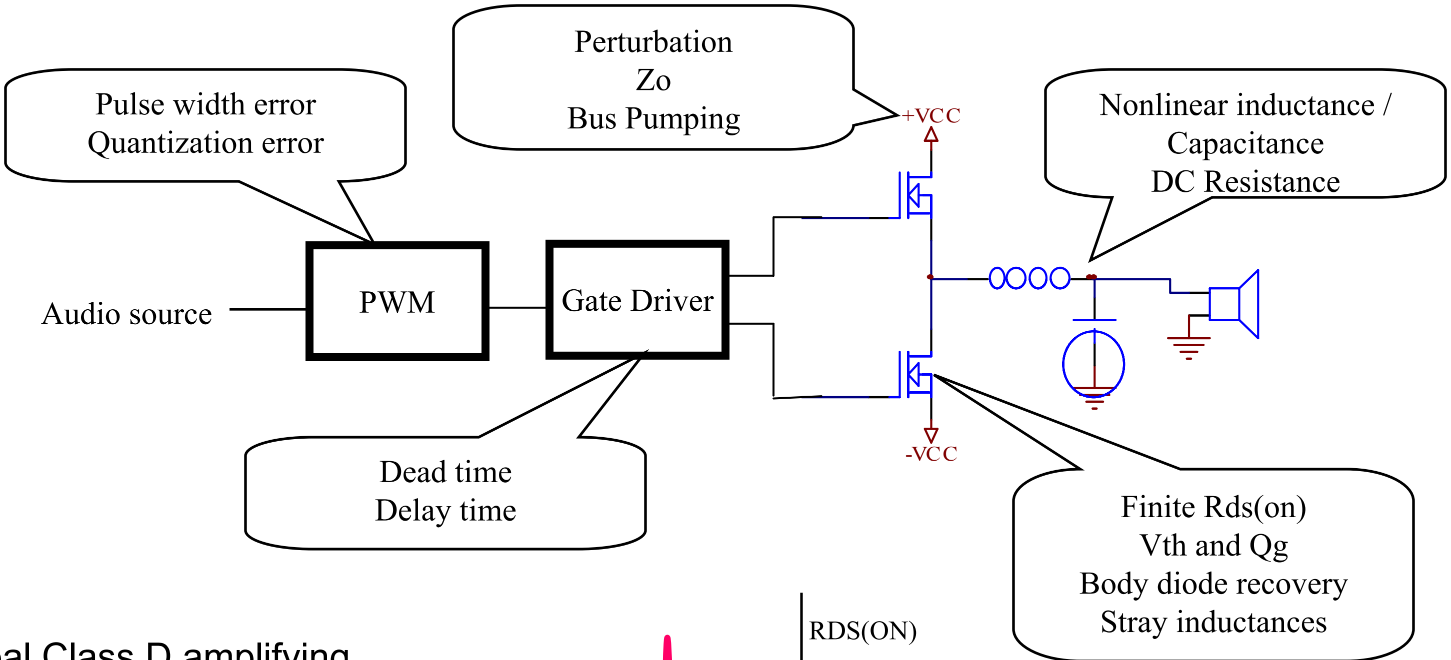


The output signal of comparator goes high when the sine wave is higher than the sawtooth.

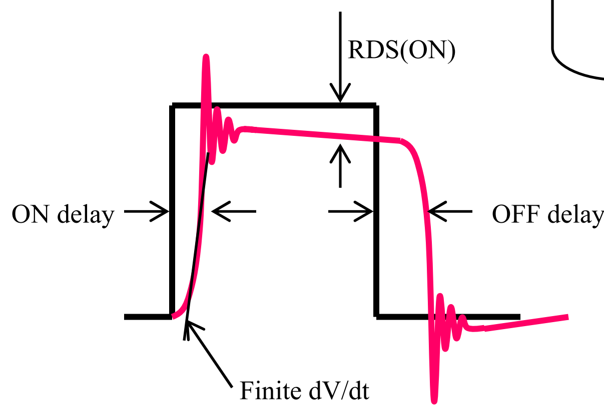


Using f_{PWM}=400kHz to modulate 25kHz sinusoidal waveform

Major Causes of Imperfection



An ideal Class D amplifying stage has no distortion and no noise generation in the audible band, along with providing 100% efficiency. However, as shown, practical Class D amplifiers have imperfections that generate distortions and noise.



0.01% of non-linearity corresponds to

10mV out of 100V DC bus

or 0.25ns out of 400kHz.

Three Difficulties in Class D Design

- **PCB Layout**

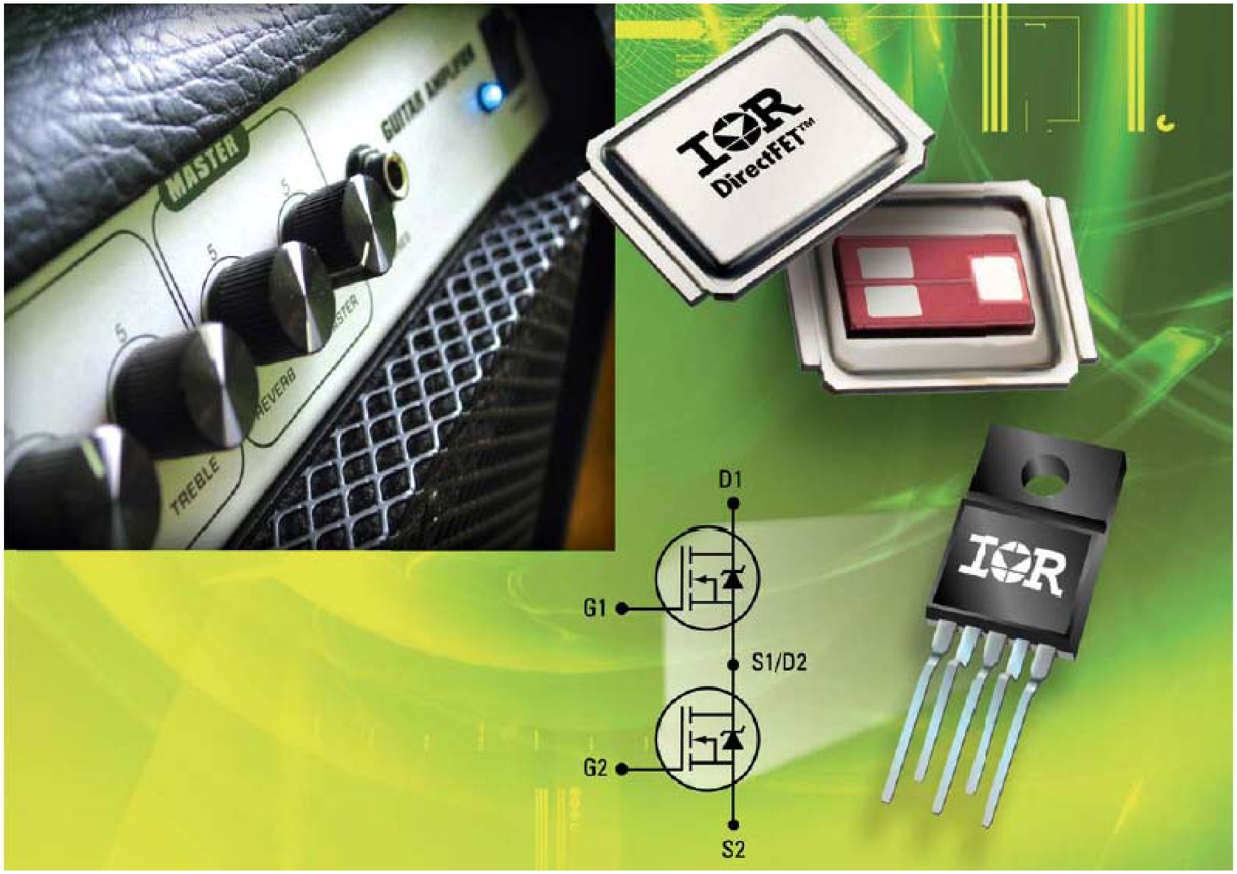
Direct-FET, Half-bridge MOSFET can eliminate influences from stray inductances.

- **Dead-time Generation**
- **Overload Protection**

Integrated Gate Driver IC can make things easier

Chapter 2 DIGITAL AUDIO MOSFET

The right power switch for Class-D audio amplifiers



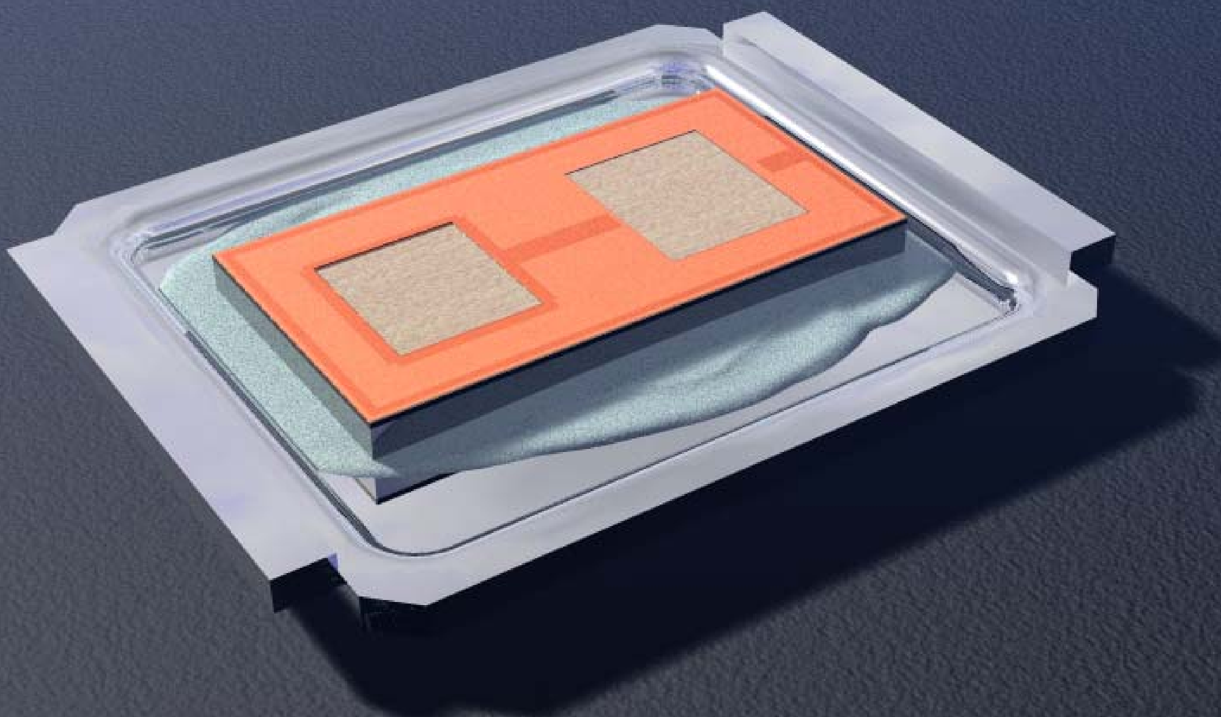
Digital Audio MOSFET introduction

- Digital Audio MOSFET is specifically designed for Class-D audio amplifier applications
- Key parameters such as $R_{DS(on)}$, Q_g, and Q_{rr} are optimised for maximizing efficiency, THD and EMI amplifier performance
- Low internal R_G distribution guaranteed for better dead time control
- New and innovative packages offer greater flexibility and performance
- These features make IR Digital Audio MOSFETs the right power switches for Class-D audio amplifiers!!

IOR International Rectifier

CLASS D AUDIO

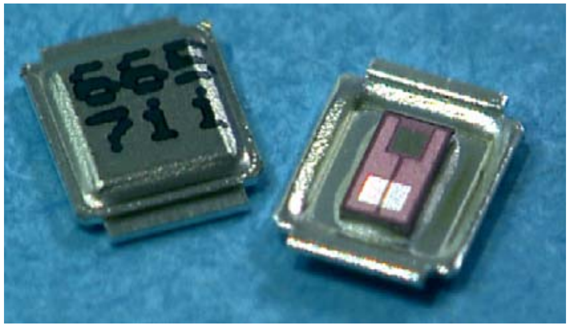
IRF6665 DirectFET®



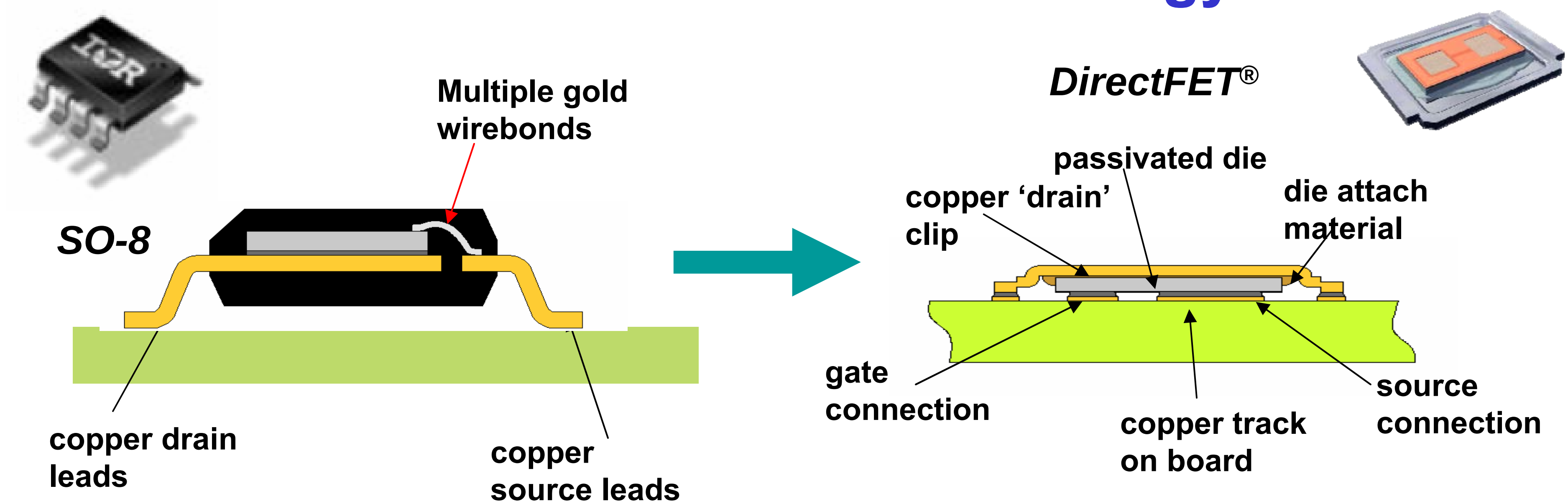
The best MOSFET for Mid-Power Class-D amplifier applications

IRF6665 Digital Audio MOSFET

- IRF6665 Digital Audio MOSFET combines the latest IR medium voltage trench silicon with the advanced DirectFET® package
- Key parameters, such as $R_{DS(on)}$, Q_g, Q_{sw}, and Q_{rr} are optimized for mid-power Class-D audio amplifier applications
- IRF6665, has all the characteristics to be the best power switch for mid-power amplifiers!!



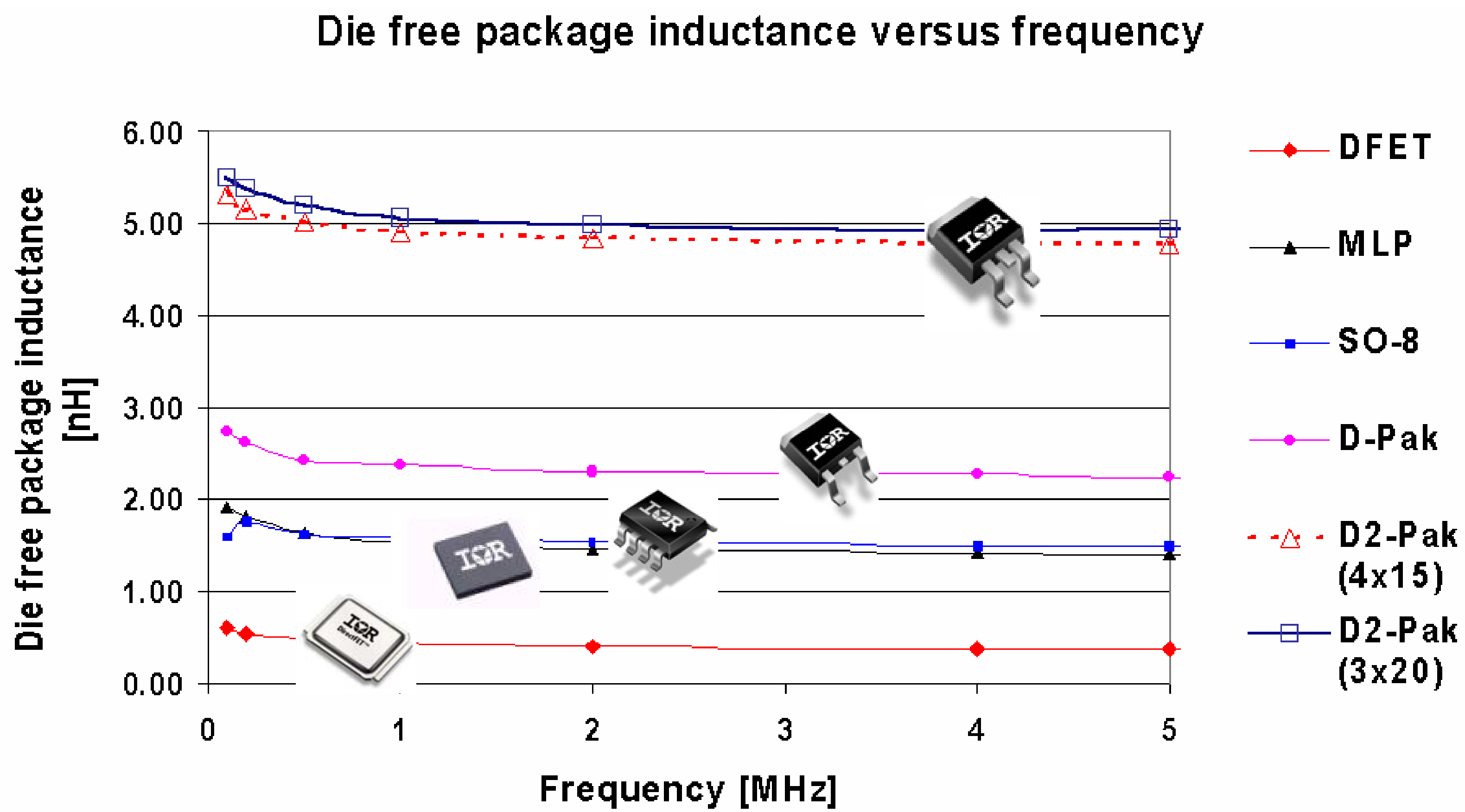
DirectFET® device technology



- Drain/source leads and wirebonds contribute to both package resistance and inductance
- Majority of heat transferred through leads to PCB board

- Remove wirebonds from package and replace with large area solder contacts
- Reduced package inductance and resistance
- Copper can enables dual sided cooling

DirectFET®: low inductance package for audio

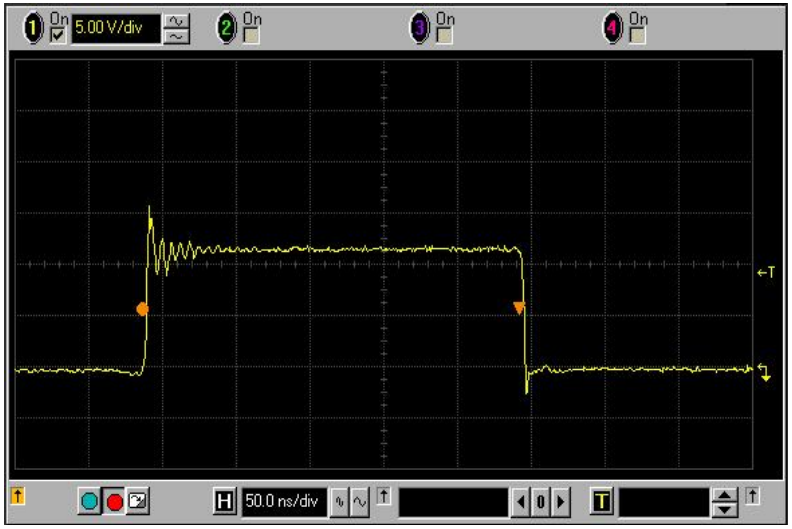


- Lower inductance at frequency than SO-8, D-Pak, MLP and D-Pak
- TO-220 inductance package is ~ 12nH

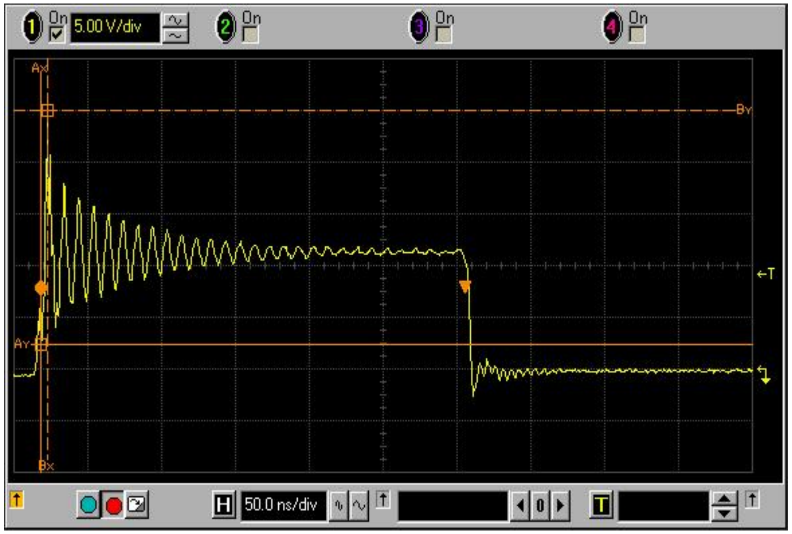
Advantages of DirectFET®: Reduce ringing

- Inductance related ringing reduced compared to SO-8
- Example below for DirectFET® and SO-8 switching 30A at 500kHz
- Silicon of the near identical active area, voltage and generation used in both packages

DirectFET® waveform



SO-8 waveform



IRF6665 for class-D audio applications

International
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DIGITAL AUDIO MOSFET

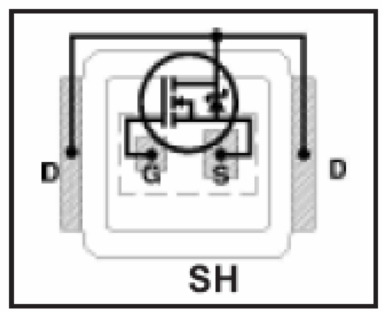
IRF6665

Features

- Latest MOSFET Silicon technology
- Key parameters optimized for Class-D audio amplifier applications
- Low $R_{DS(on)}$ for improved efficiency
- Low Q_g for better THD and improved efficiency
- Low Q_{rr} for better THD and lower EMI
- Low package stray inductance for reduced ringing and lower EMI
- Can deliver up to 100W per channel into 8Ω with no heatsink ⑧
- Dual sided cooling compatible
- Compatible with existing surface mount technologies
- Lead and Bromide Free

Key Parameters

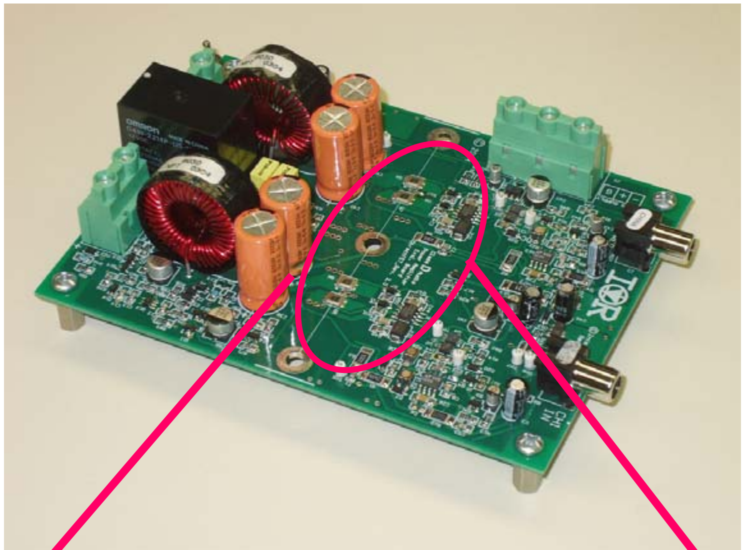
Parameter	Min	Typ	Max	Units
V(BR)DSS	100	-	-	V
RDS(ON) @ VGS = 10V	-	53	62	mOhms
Qg	-	8.4	13.0	nC
Qgd	-	2.8	-	nC
Qsw	-	3.4	-	nC
RG (int)	-	1.9	2.9	Ohms
VGS(TH)	3	-	5	V




DirectFET™ ISOMETRIC

- Refer to IRF6665 datasheet for further details

IRF6665 DirectFET® Evaluation Board



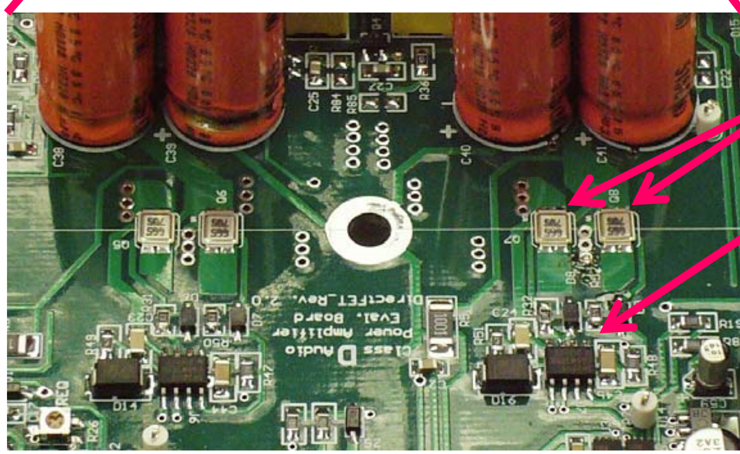
Spec:

Power Supply ±35.0V

Output Power 150W+150W, 4Ω

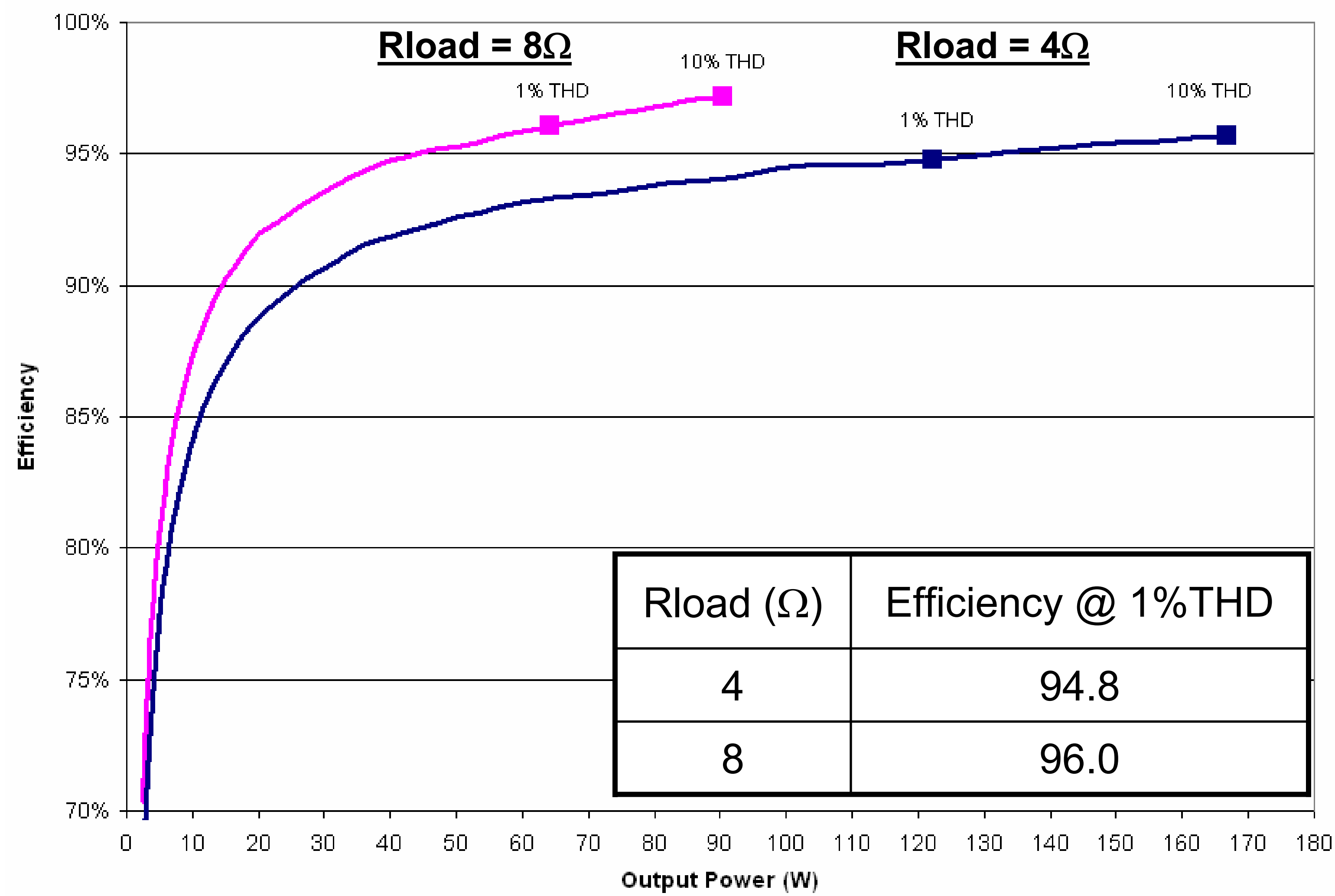
MOSFET IRF6665

Gate Driver IR2011S



Efficiency Data

Test Conditions: Half-Bridge Configuration, Vbus = +/- 35V, fswitching = 395kHz, finput = 1kHz, Rload = 4 and 8 Ohms

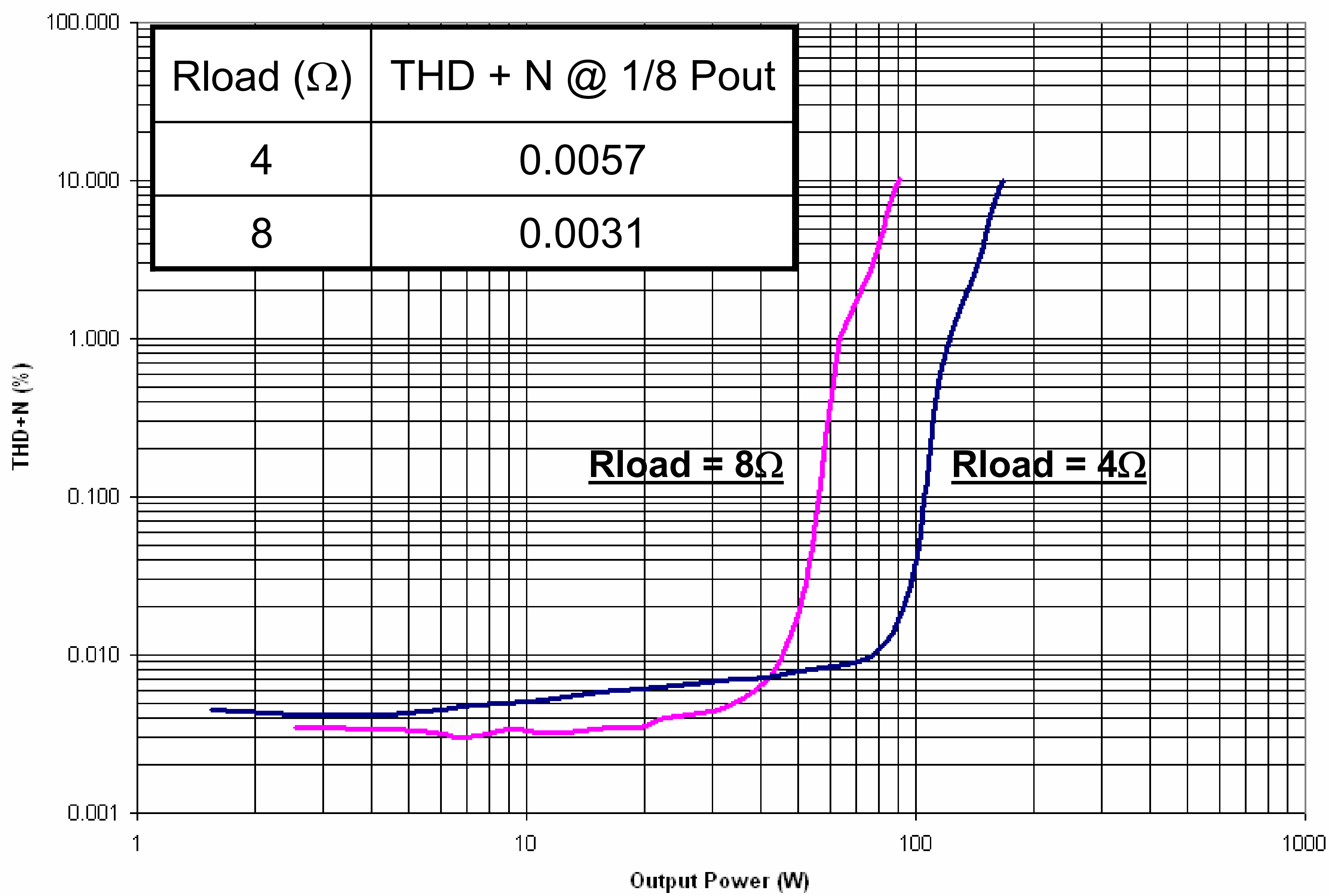


Rload (Ω)	Efficiency @ 1%THD
4	94.8
8	96.0

THD+N Data

Test Conditions: Half-Bridge Configuration, Vbus = +/- 35V, fswitching = 395KHz, finput = 1KHz, Rload = 4 and 8 Ohms

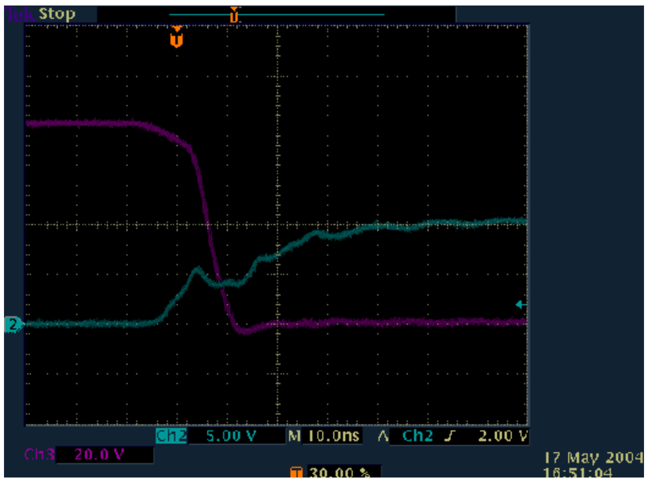
Rload (Ω)	THD + N @ 1/8 Pout
4	0.0057
8	0.0031

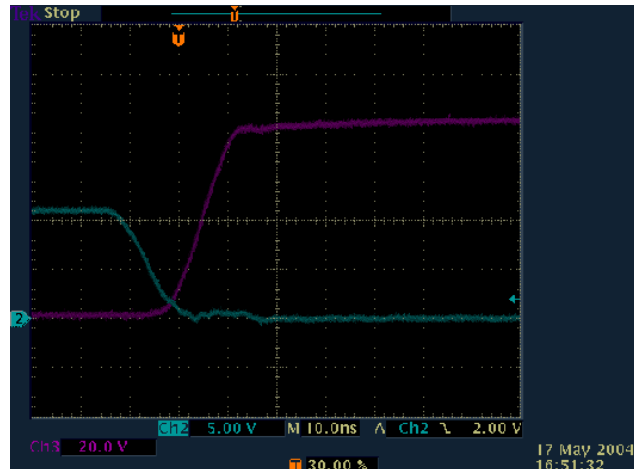


VDS Switching Waveforms

- DirectFET® package shows cleanest and fastest (approx. three times faster) switching waveforms than amplifier with TO-220 package.
- Same IRF6665 MOSFET die is tested in both packages

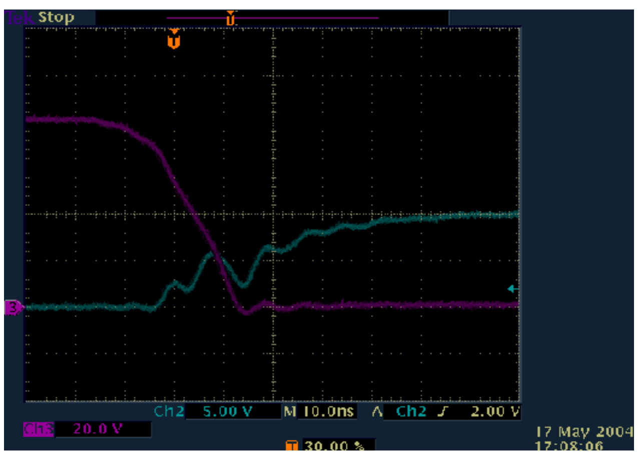
DirectFET® Package

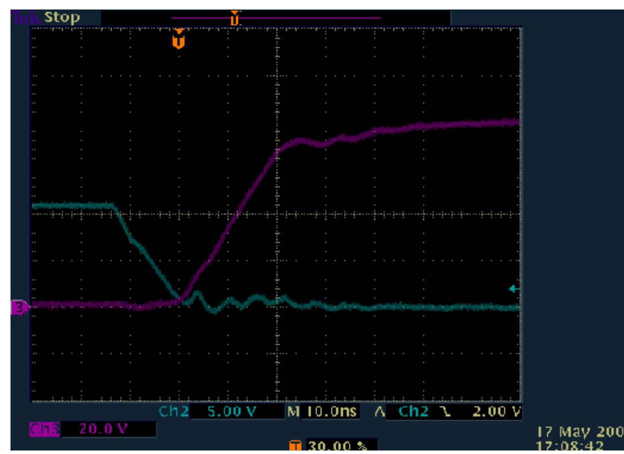




Blue : V_{GS}
Pink : V_{DS}

TO-220 package

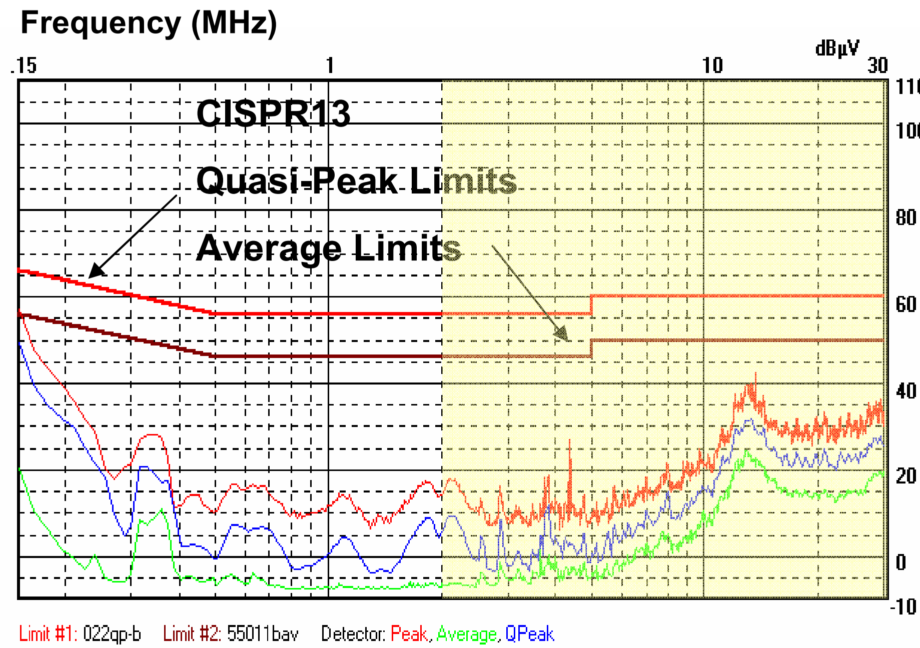




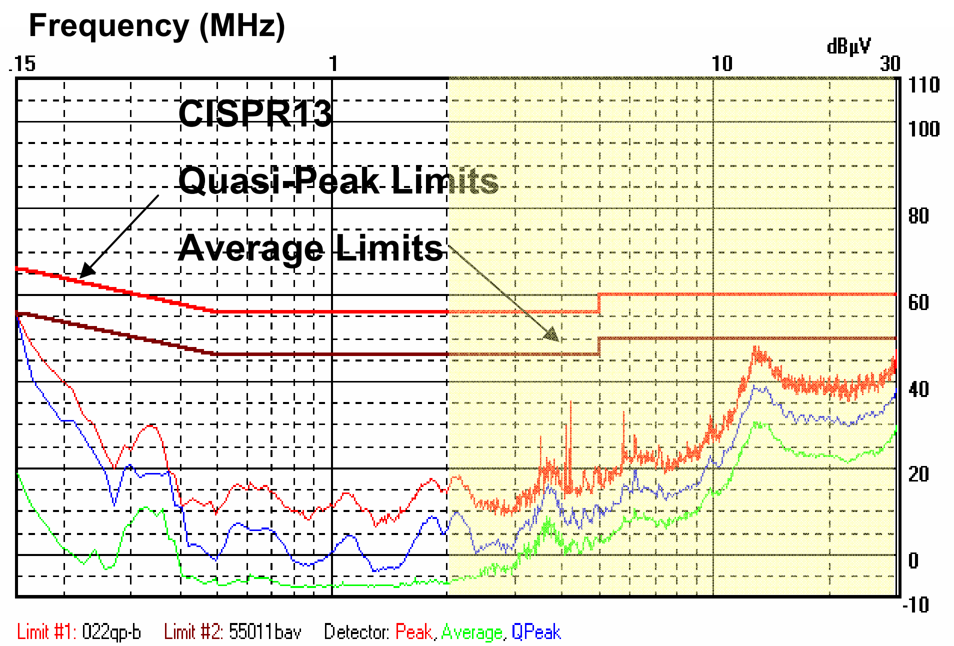
EMI Data @ 1/8 Pout Condition (12.5W)

- DirectFET® and TO-220 with the same IRF6665 silicon die
- MosFET devices with no heatsink
- No shielded room
- Over 2MHz, DirectFET® amplifier shows approximately 9dB lower noise than TO-220 amplifier
- Under 2MHz, background noise is dominant

DirectFET®



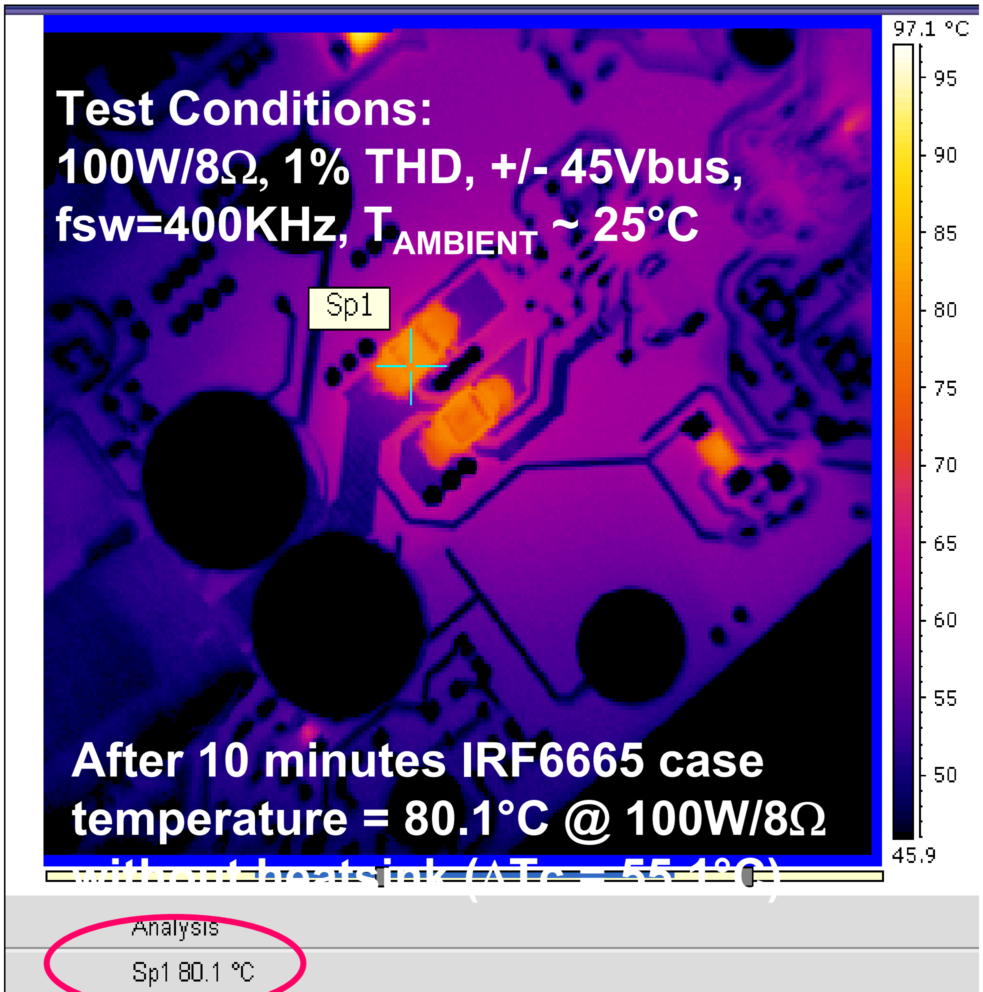
TO-220



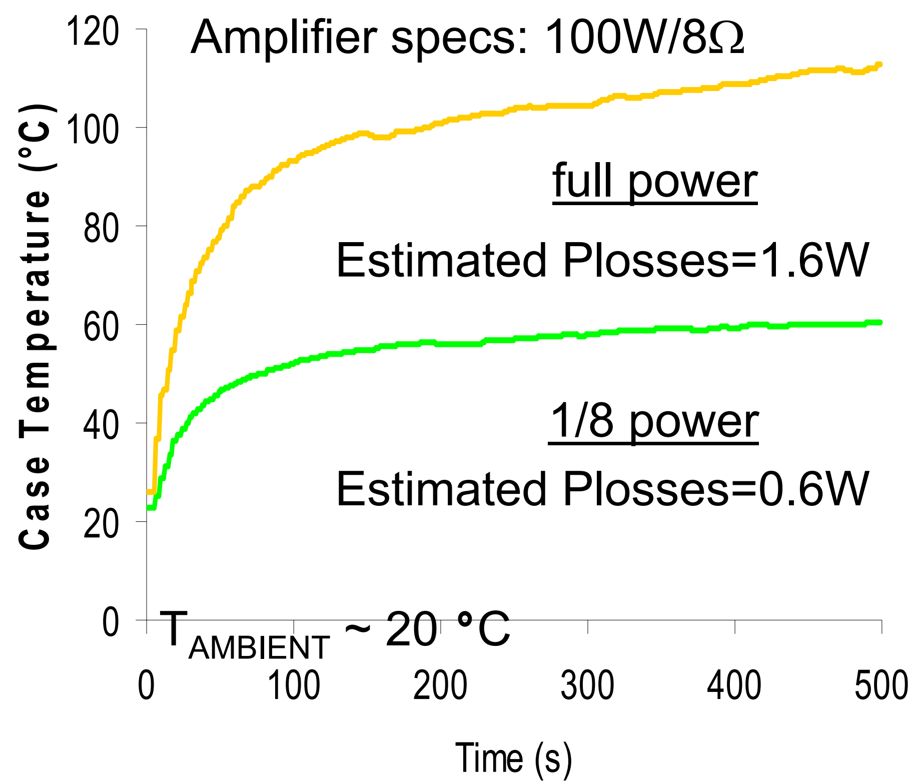
Thermal Performance

No Heatsink

Typical Case Scenario



Worst Case Scenario



Full Power: T_C=104°C @ 5min (ΔT_C=83°C)

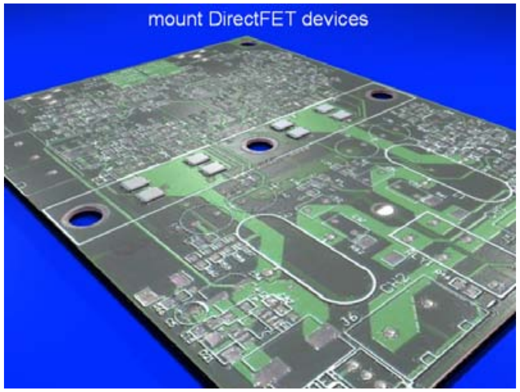
1/8 Power: T_C=58°C @ 5min (ΔT_C=39°C)

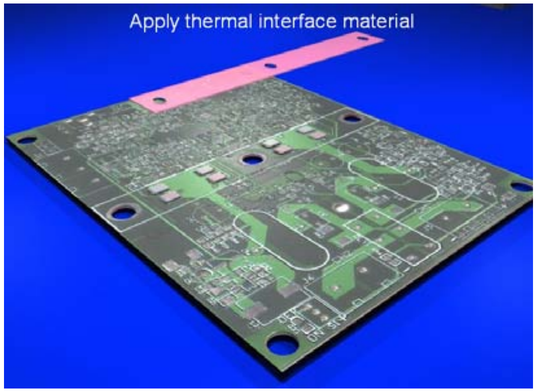
Assembling IRF6665 in audio Class-D circuits

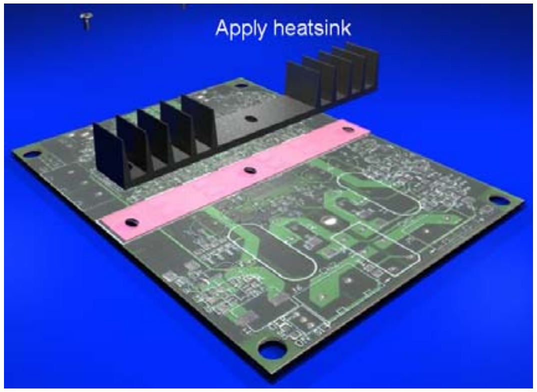
- Stencil on solder paste
- Pick and place devices onto pads
- Re-flow devices

If additional heatsink is needed for higher power,

- Place thermal interface material over devices
- Place heatsink over device/thermal interface stack
- Secure heatsink in place with screws
- PCM burned in to wet out interface between can and heatsink
- Screw torques reset when assembly has cooled



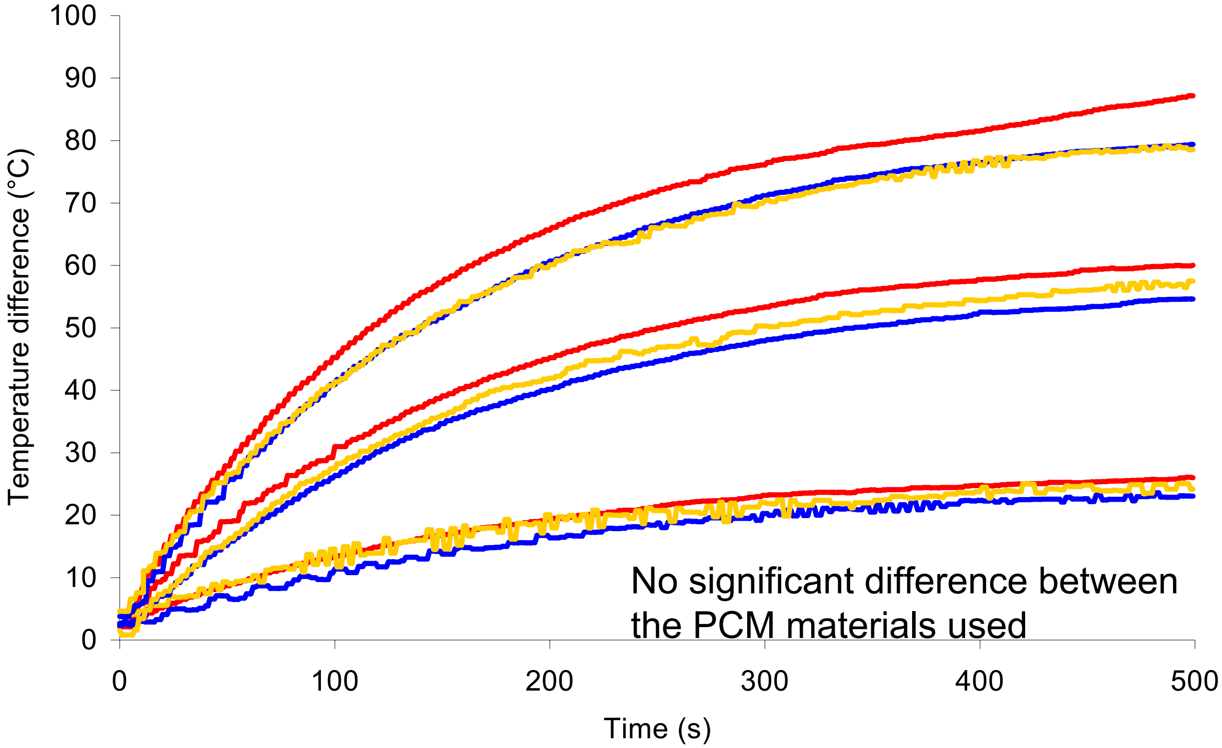




Thermal Performance with Heatsink

- **Individual DirectFET® MOSFET audio reference boards assembled with 3 different phase change materials**
- **Heatsink applied to assembly**
  - Fischer SK04, 3.8”X0.6”, 0.6” extrusion, black anodised, 3°CW^{-1}
- **Constant power applied to device junctions to simulate 100W amplifier operation:**
  - Normal operation conditions (1/8 full output power) into 4Ω and 8Ω
  - Full output power into 4Ω and 8Ω
- **Case temperature was monitored before and during application of power to the junctions with thermocouples applied between can and heatsink**

ΔT_{CASE} versus time



100W into 4Ω
Power/device* = 2.4W

100W into 8Ω
Power/device* = 1.6W

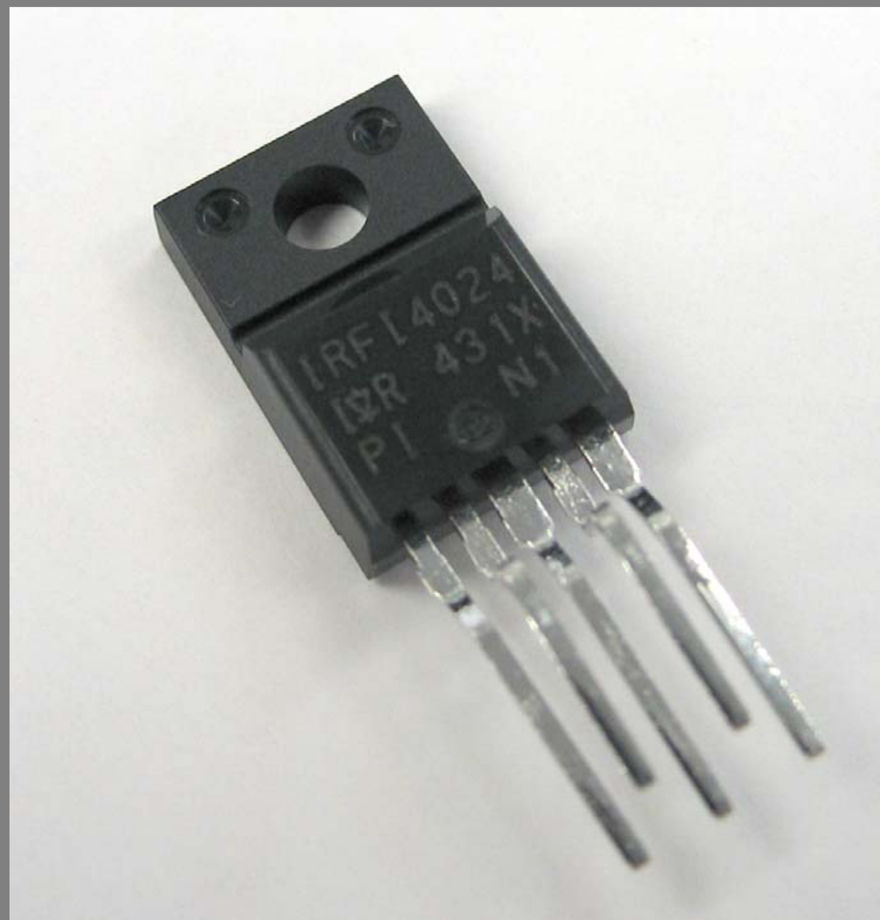
12.5W into 4Ω & 8Ω
(1/8 of 100W)
Power/device* = 0.6W

Amplifier Conditions	Plosses* per device	Temperature rise (°C) after 5 min		
		Material A	Material B	Material C
12.5W (1/8) into 4 & 8Ω	0.6	22.1	24.8	23.4
100W into 8Ω	1.6	52.7	58.2	55.1
100W into 4Ω	2.4	77.1	82.8	76.4

(*) Estimated Plosses @ worst case scenario

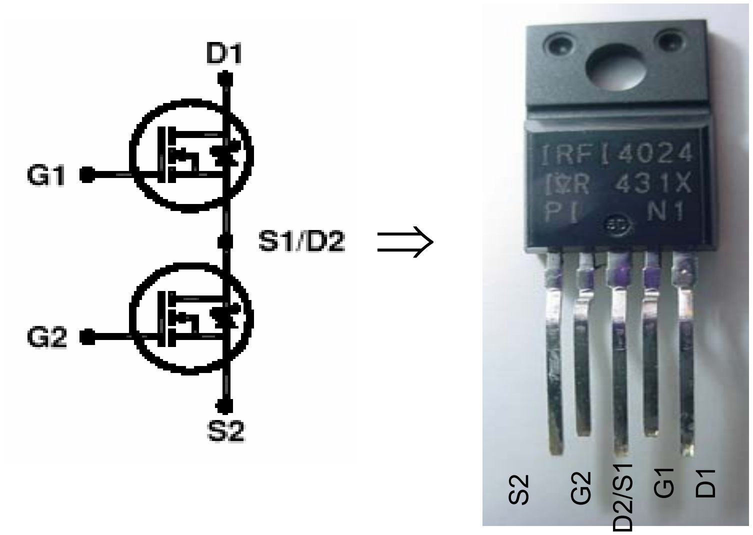
International Rectifier CLASS D AUDIO

Half-Bridge Full-Pak



Another Innovative Package for Class D Audio Amplifier Application

Half-Bridge Full-Pak



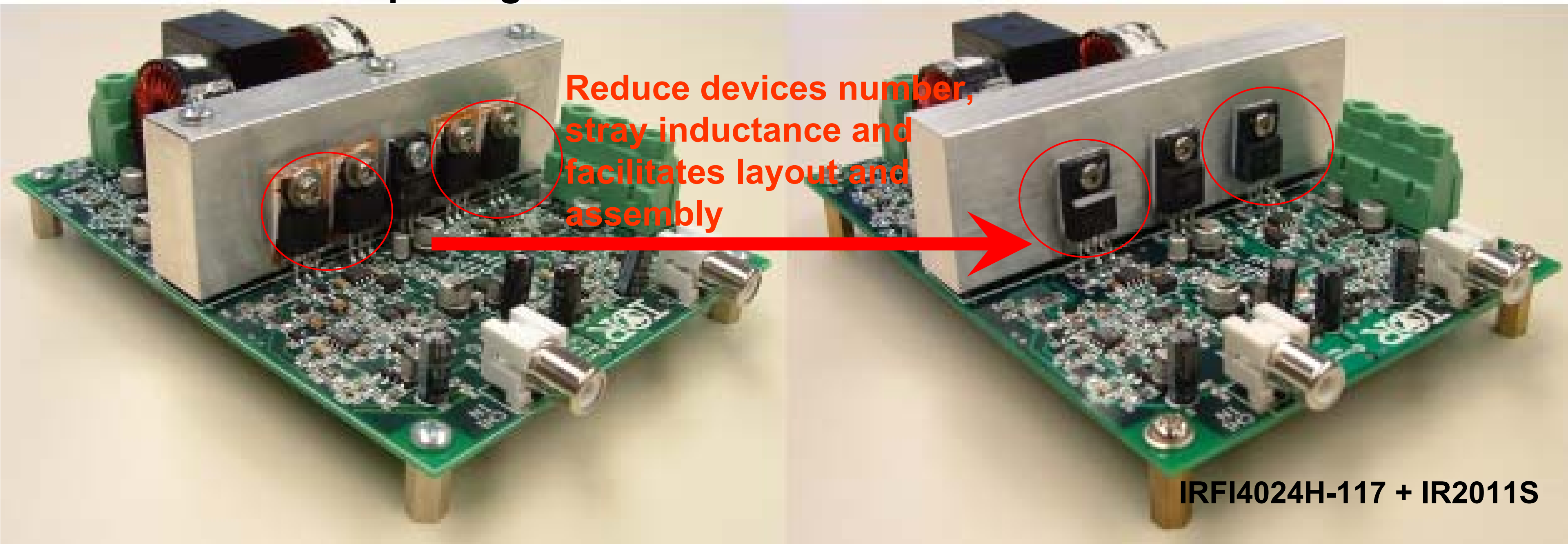
TO-220 Full-Pak

5 PIN

- **55V, 100V, 150V and 200V devices to be released on Q3 '06**
  - **55V: IRFI4024H-117**
  - **100V: IRFI4212H-117**
  - **150V: IRFI4019H-117**
  - **200V: IRFI4020H-117**

Half-Bridge Full-Pak Features

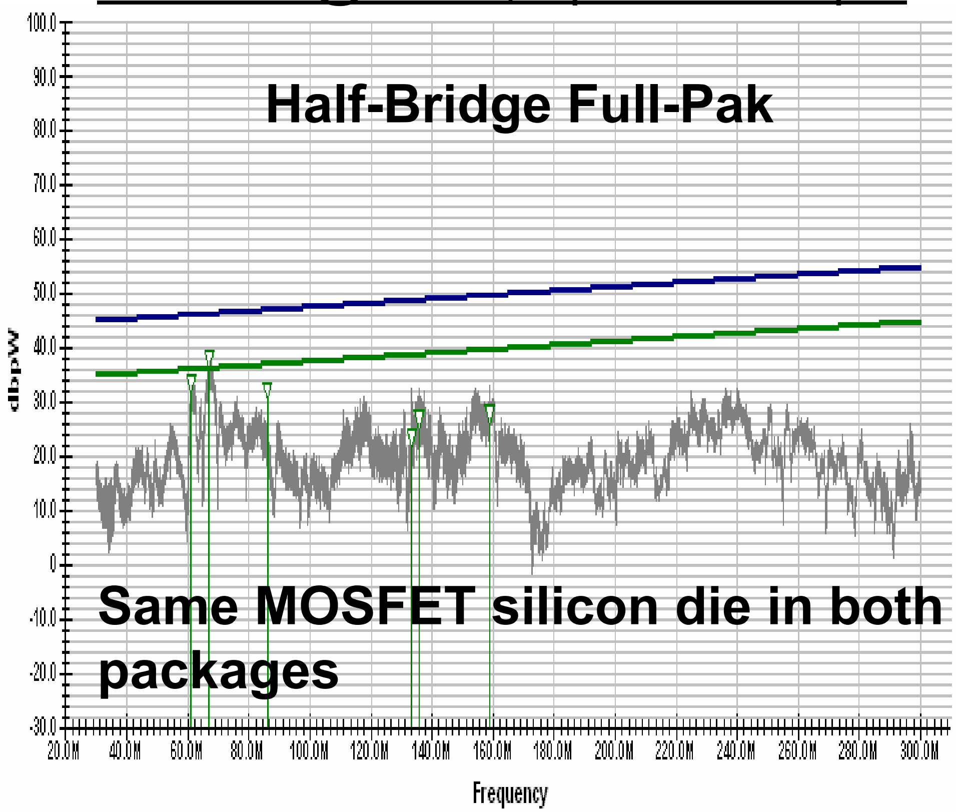
- Integrated Half-Bridge Package
- Reduces the part count by half
- Reduced package inductance improves EMI performance
- Facilitates better PCB layout
- Enables single layer PCB layout in combination with IR2011S
- Low $R_{G(int)}$ distribution for better dead time control
- Lead-Free package

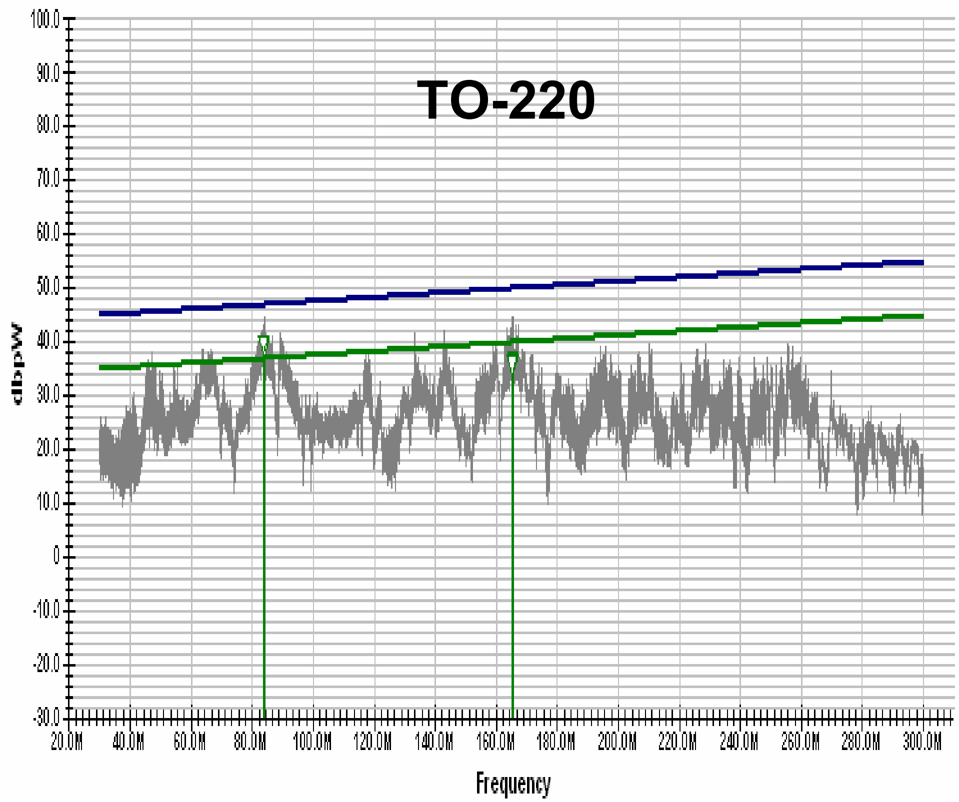


Disturbance Power
Half-Bridge Full-Pak vs. TO-220 (single die)

- **Half-Bridge Full-Pak amplifier shows better performance than TO-220 amplifier. Approximately 10dB lower disturbance power level.**

180VAC @ 50Hz, Speaker Output





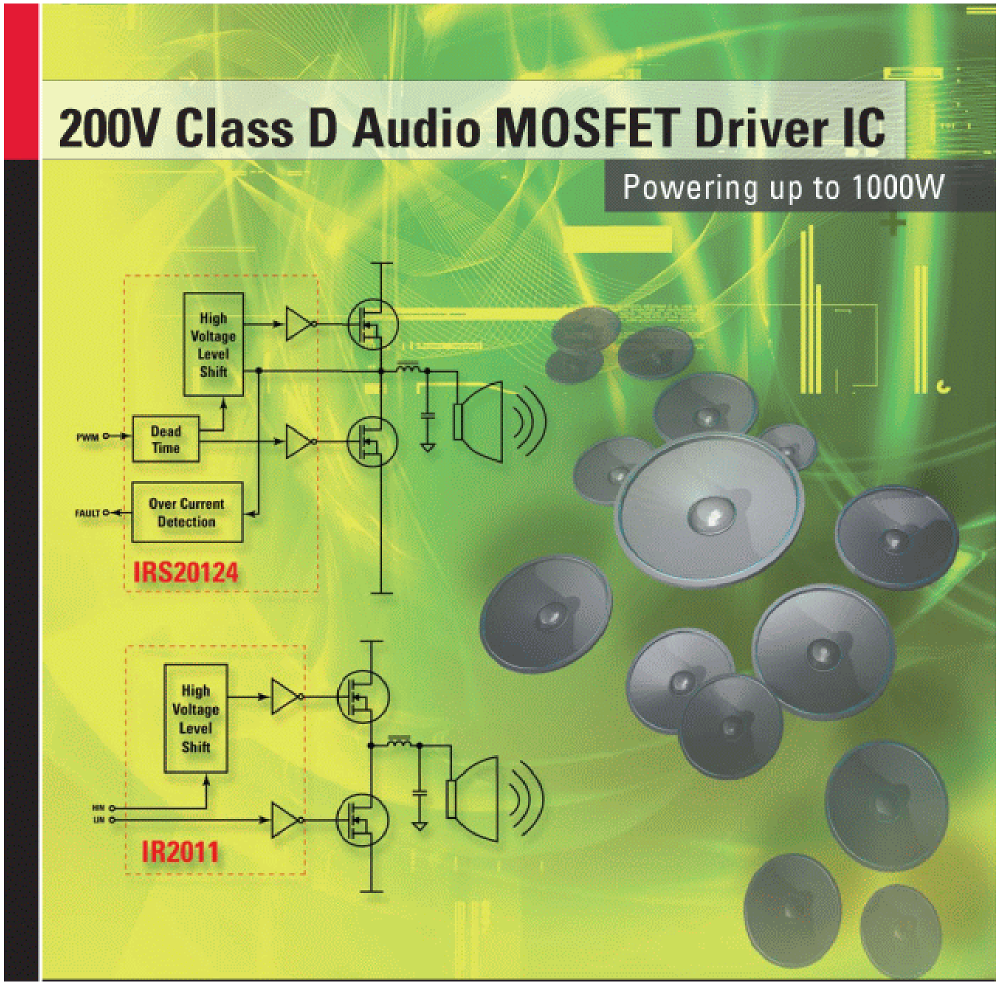
Summary

- DirectFET® devices are ideal candidates for use in Class-D audio amplifier applications
- Evaluations of IRF6665 in Class-D audio amplifier demonstrated improved efficiency, THD, and EMI
- Utilising DirectFET® technology reduces EMI compared to TO-220 packages
- Thermal evaluations demonstrated that IRF6665 can deliver up to 100W per channel into 8Ω with no heatsink
- Half-Bridge Full-Pak features make this device an excellent option for Class-D audio amplifier applications
  - Integrated half-bridge package reduces the part count by half
  - Low package inductance improves EMI performance
- Digital Audio MOSFET is the right switch for Class-D audio amplifiers!!

Conclusion 1

- **With IR's DirectFET® technology, Class D amplifier reaches the point where 100W amplifier can be built without heat sink**
- **Optimum package provides the best audio performance along with minimum EMI emissions**
- **Optimum silicon design provides the best efficiency over 95%**

Chapter 3 DIGITAL AUDIO Gate Driver



Protected DIGITAL AUDIO Gate Driver IC
IRS20124

•Programmable Discrete Dead-time (PAT.Pending)

•Programmable Bi-directional Over Current Sensing (PAT.Pending)

•200V high voltage ratings to deliver up to 1000W output power in Class D audio amplifier applications

•Simplifies design due to integrated dead-time generation and bi-directional over current sensing

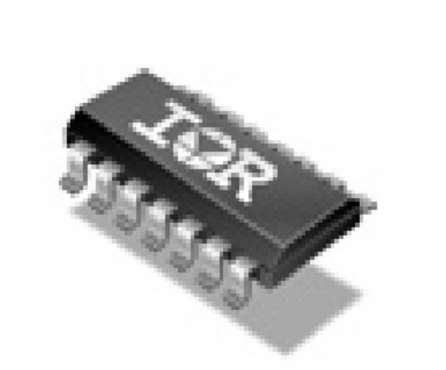
•Optimized and compensated preset dead-time selections for improved THD performances over temperature and noise

•Shutdown function to protect devices from overloaded conditions

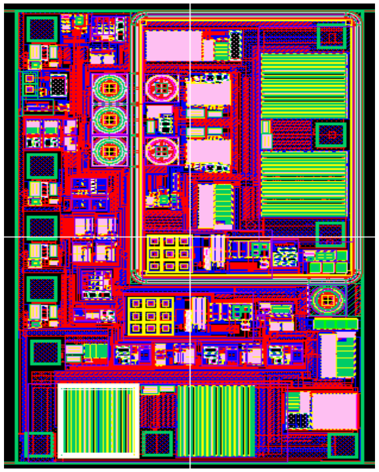
•Operates up to 1MHz

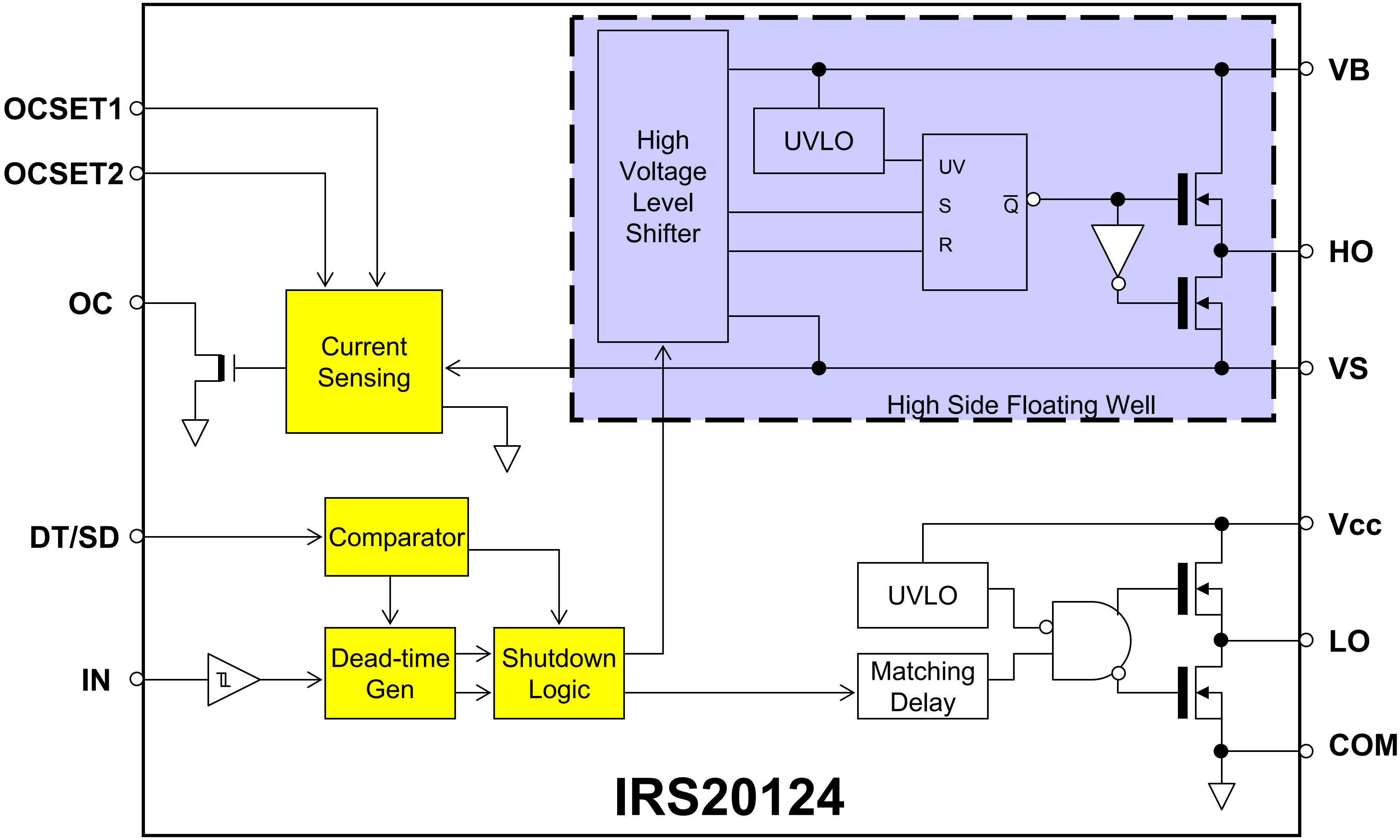
•3.3V/5V logic compatible input

V_{SUPPLY}	200V max
I_O	+/-1.0A / 1.2A
Selectable Dead-time	15/25/35/45nS
Prop Delay time	70ns



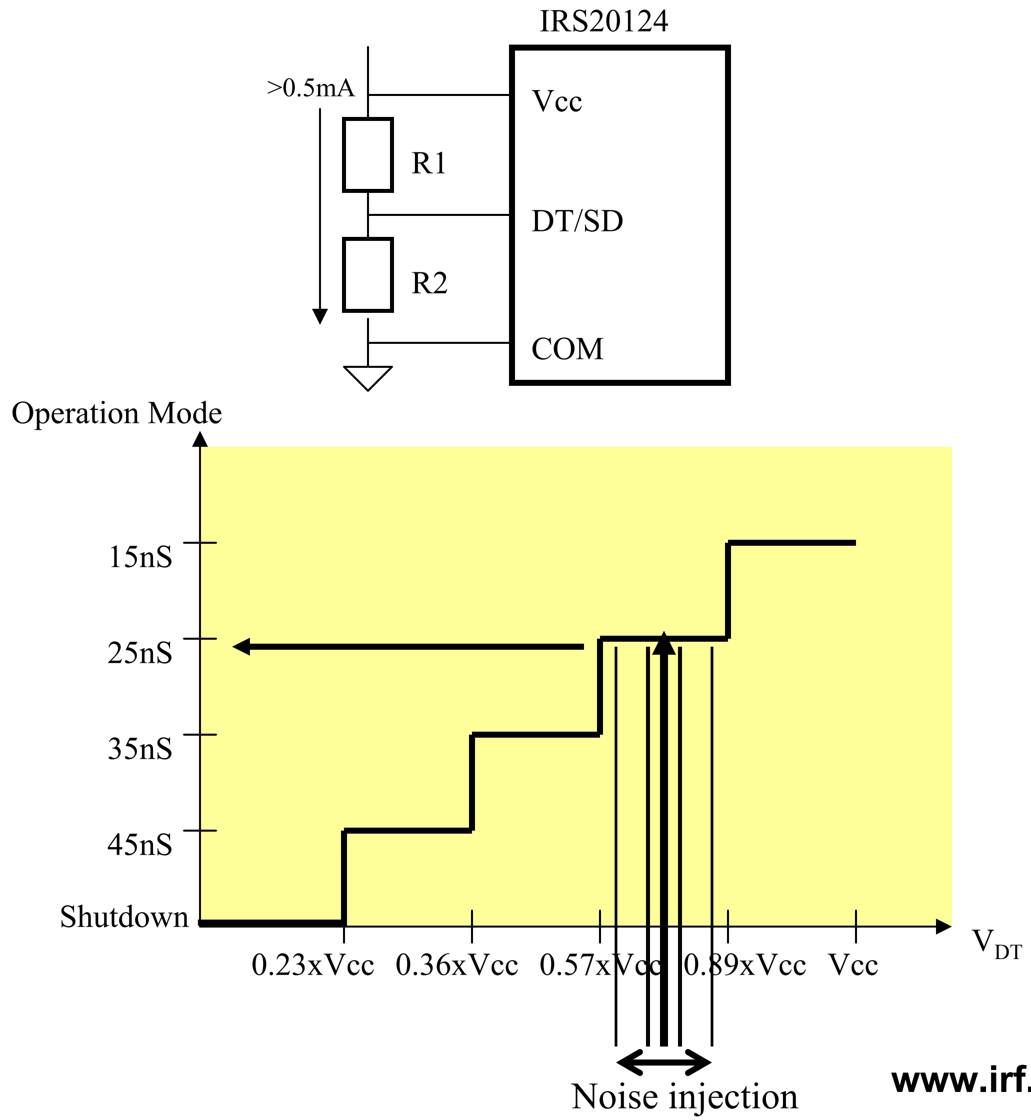
14pin SOIC



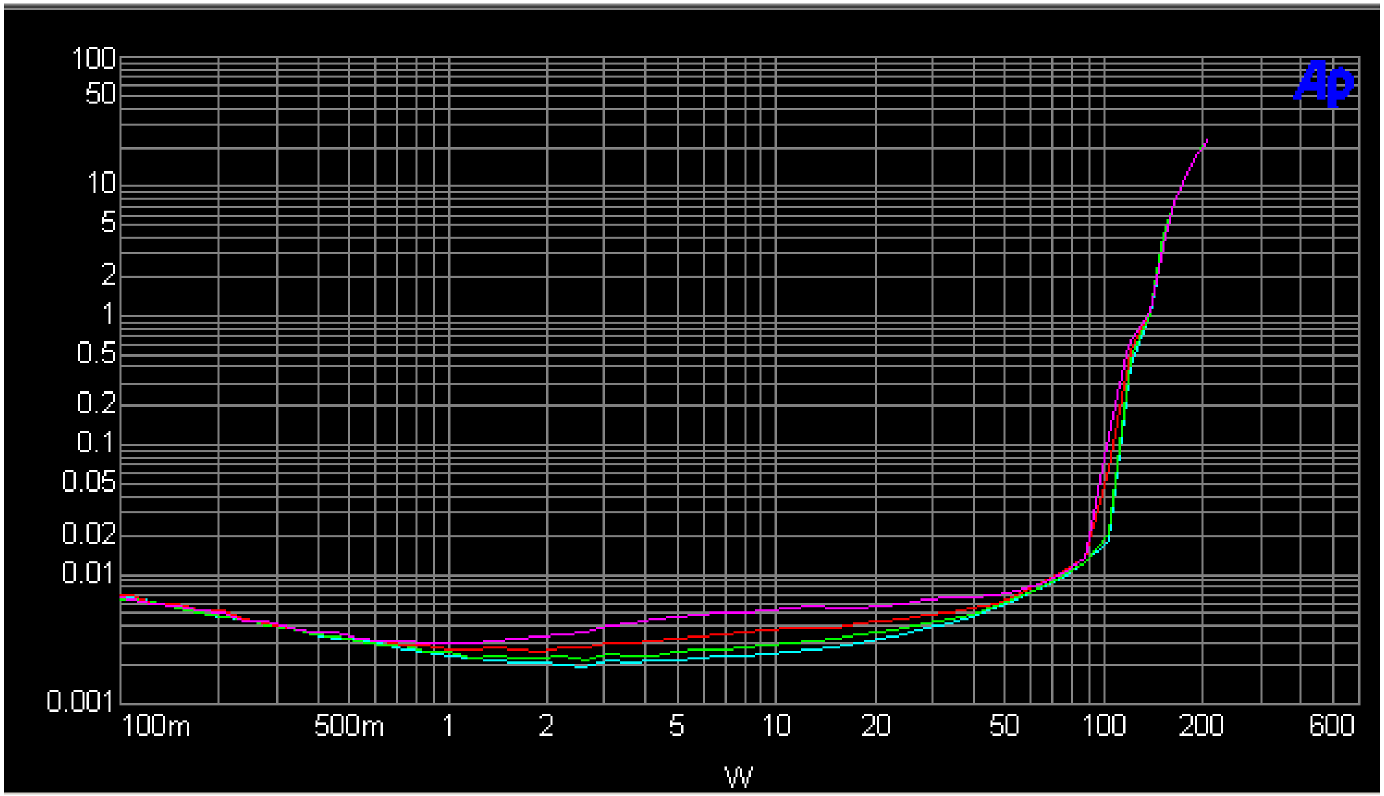

VB
OCSET1
OCSET2
High Voltage Level Shifter
UVLO
UV
S
R
Q
HO
OC
Current Sensing
VS
High Side Floating Well
DT/SD
Comparator
Vcc
UVLO
LO
IN
Dead-time Gen
Shutdown Logic
Matching Delay
COM
IRS20124

Discrete Dead-time

The discrete dead-time method sets a dead-time by selecting one of the preset values from outside of the IC. Comparing with previous program method, the discrete dead-time can provide a precise dead-time insertion, regardless of noise injection in DT pin. Thus, the dead-time setting value can be set tighter, which is highly beneficial for the THD performance in Class D applications.



IRS20124 THD+N Performance



Sweep	Trace	Color	Line Style	Thick	Data	Axis	Comment
1	1	Cyan	Solid	1	Anlr.THD+N Ratio	Left	DT1
2	1	Green	Solid	1	Anlr.THD+N Ratio	Left	DT2
3	1	Yellow	Solid	1	Anlr.THD+N Ratio	Left	
4	1	Red	Solid	1	Anlr.THD+N Ratio	Left	DT3
5	1	Magenta	Solid	1	Anlr.THD+N Ratio	Left	DT4

V_{CC}: ±35.0V

Gate Driver: IRS20124

MOSFET: IRFB4212

f_{PWM} = 400kHz

Note that low THD+N characteristic shows quiet noise floor due to clean and stable switching timings.

Dead-time Settings:

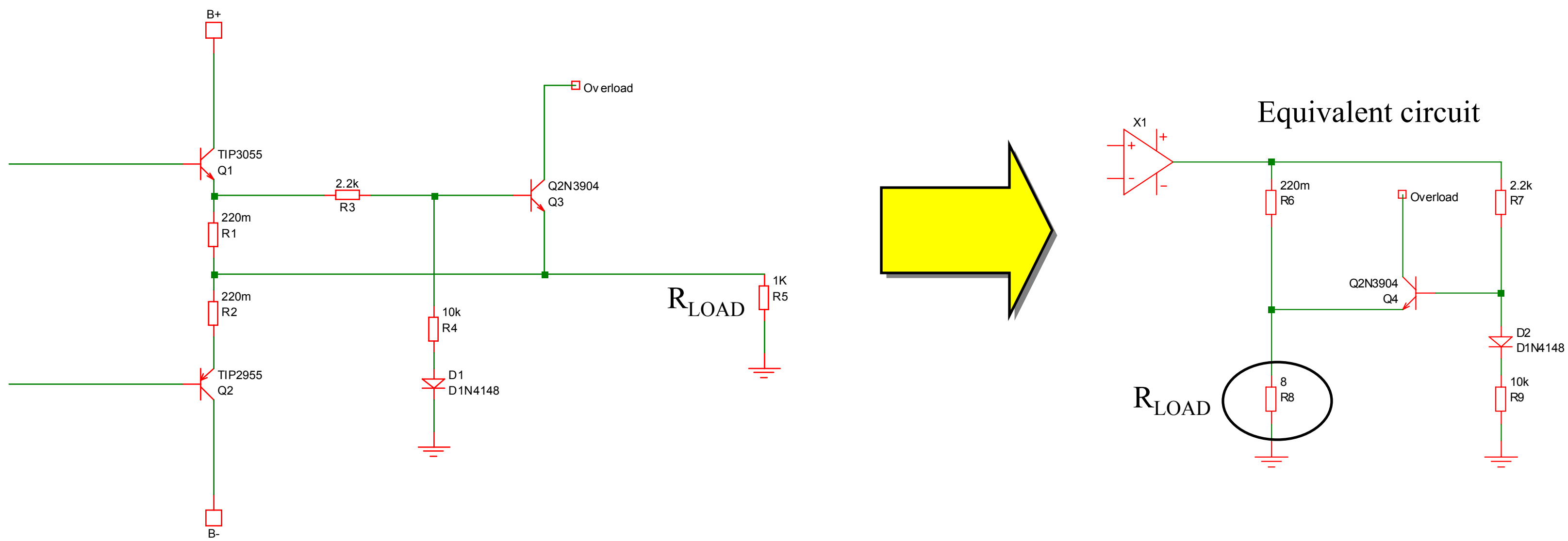
DT1 = 15ns

DT2 = 25ns

DT3 = 35ns

DT4 = 45ns

Overload Protection in Class AB



When a Class AB amplifier has a shorted load, the load current can ramp up rapidly. The voltage across the device is fixed to the bus voltage.

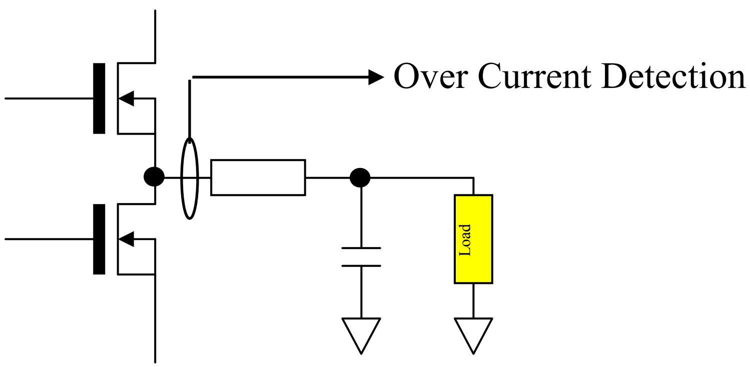
➔The loss in the device is enormous amount

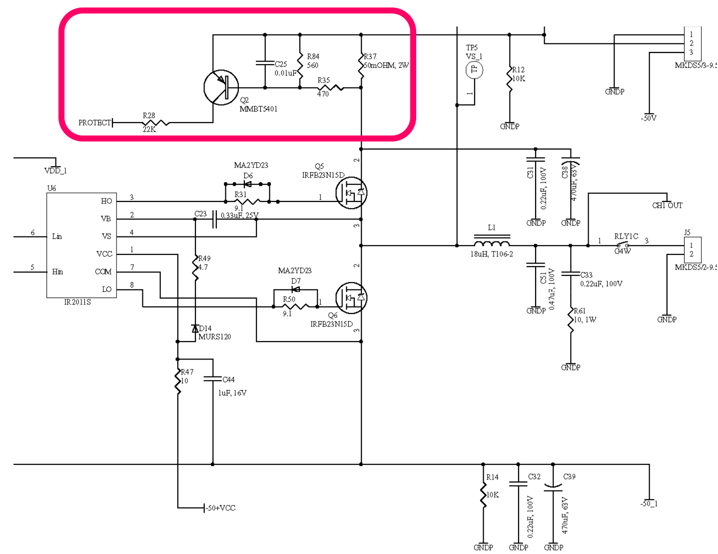
➔ **The power devices can not be protected with over current detection method**

Therefore an impedance bridge has been commonly used, which has following drawback;

• Reactive components in the load impedance, which is common in realistic loudspeakers, causes false protection

Overload Protection in Class D





When a Class D amplifier has a shorted load, there still is a LPF inductor in between the load and the amplifier. Therefore, the load current ramps up at a rate of Vo/L.

The loss in the device is determined by the $R_{DS(ON)}$ and the load current.

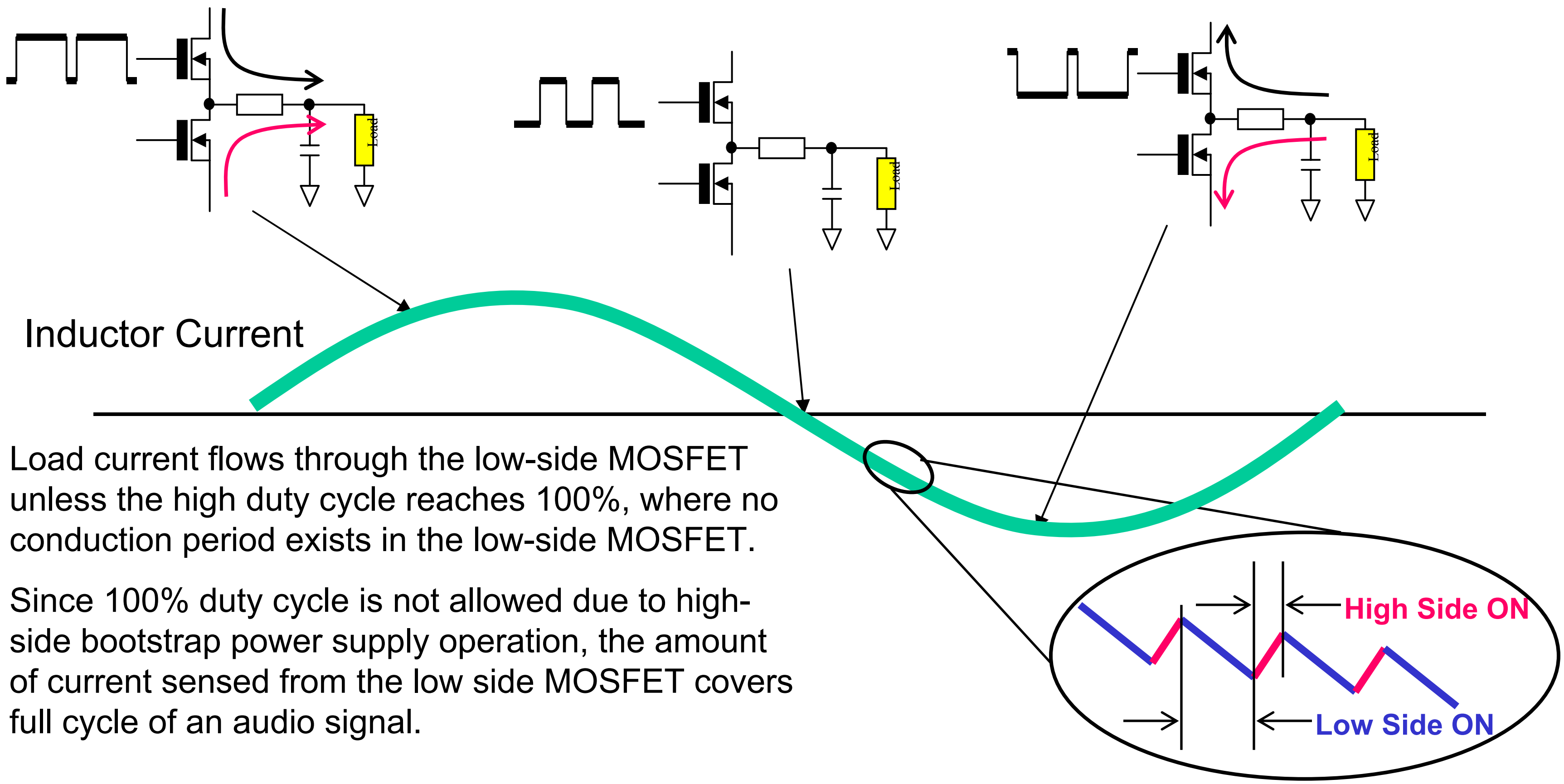
➔Over current detection works very good in Class D

Benefits from over current detection;

• Trip level is independent of phase shift in the load current

• The amplifier can sustain any instantaneous low load impedance until the load current reaches the trip level

Why Bi-Directional CS?



Load current flows through the low-side MOSFET unless the high duty cycle reaches 100%, where no conduction period exists in the low-side MOSFET.

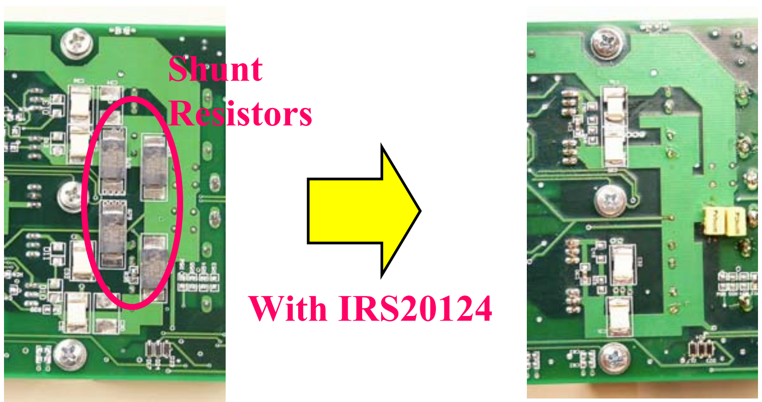
Since 100% duty cycle is not allowed due to high-side bootstrap power supply operation, the amount of current sensed from the low side MOSFET covers full cycle of an audio signal.

Benefits of Bi-Directional CS

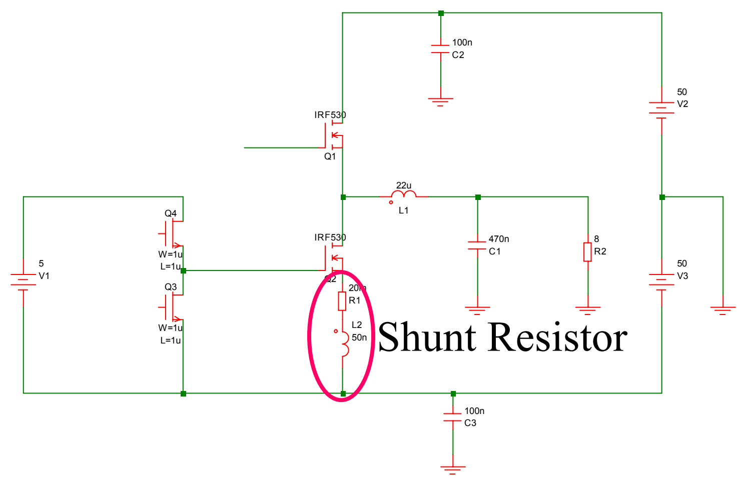
More than just cost savings…

Bi-directional current sensing provides following technical benefits.

- **Minimum stray inductance in power stage current path due to no additional current sensing components in the path**
- **No influences in measured current from gate charge current and reverse recovery charge current**
- **Positive Temp/Co in $R_{DS(ON)}$ reduces the trip level at high junction temperature in real time**

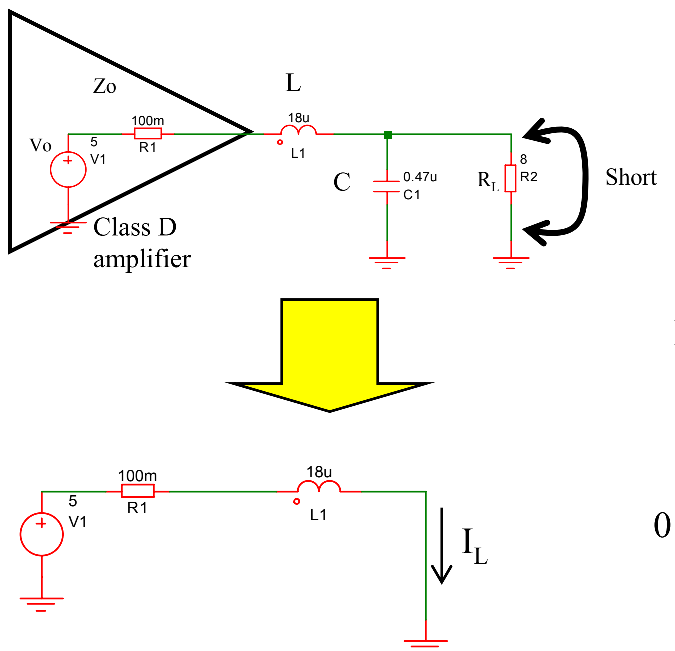


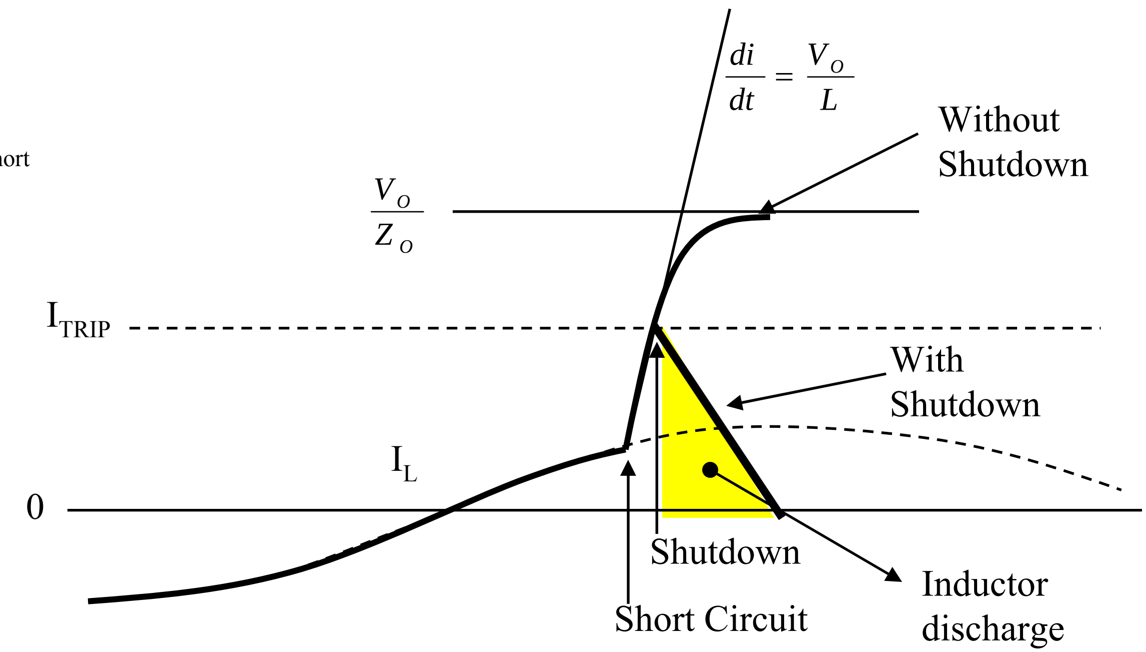
Conventional Current Sensing



- Adding a shunt resistor causes ringing by adding stray inductances.
- The current includes gate charge/discharge current and reverse recovery charge current.
- Imbalance of effective $R_{DS(ON)}$ in high and low sides causes distortion.

What happens in the Short Circuit Event?





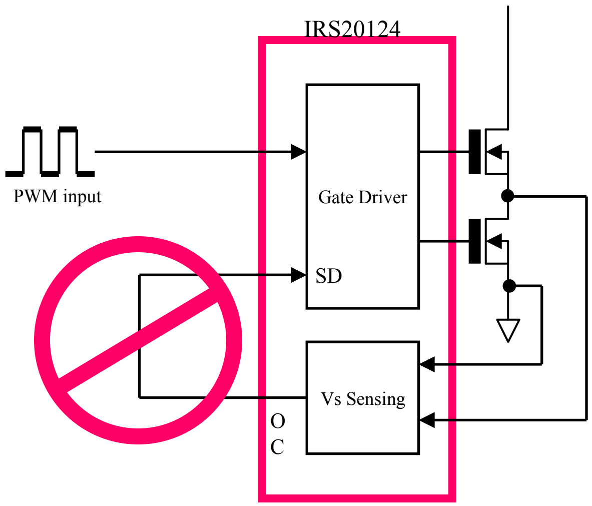
Now the Class D amplifier is driving an inductor in the LPF. Note that the audio frequency components induce quite large volt-second feeding into the inductor, causing excessive inductor current in the event of short circuit load.

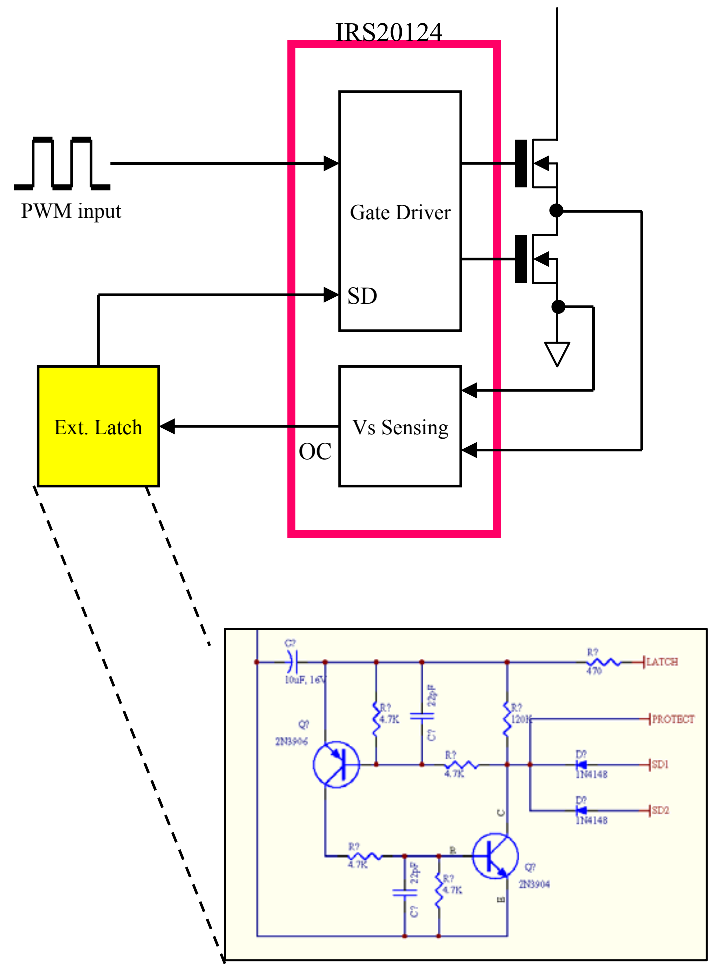
When short circuit occurs, the load current starts to ramp up quickly with a gradual rate of Vo/L. Since an inductor is in between the amplifier and the load, short current may not exceed the trip level.

A junction temperature at the end of the protection event can be estimated by using a thermal transient model in IR's Digital Audio MOSFET to ensure the functionality.

After the shutdown, the energy stored in the inductor discharges to the power supply, only the waveform of the current contributes the loss in the MOSFET.

How to Design with OC Function



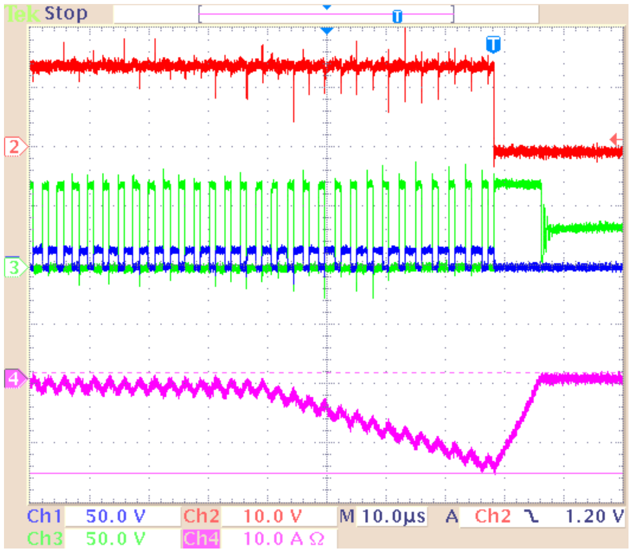


With the OC pin connected to DT/SD pin, the output signal out of OC at the event of over current will be removed by its output itself when the IRS20124 goes into shutdown mode. This could cause a hiccup in the protection sequence.

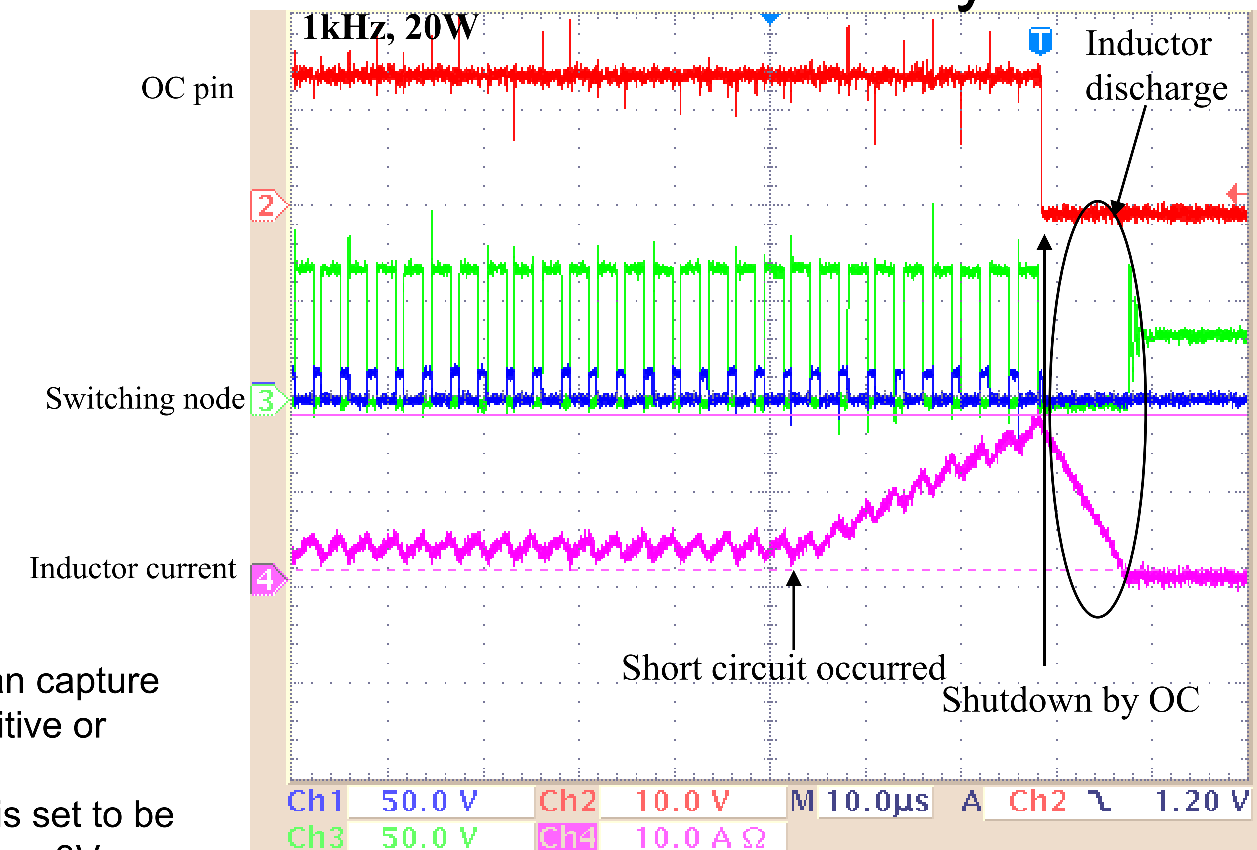
One simple way to assure shutdown upon an over current detection is to attach a latch circuitry onto the OC pin, as shown.

IRS20124 OC Functionality

In Negative Half Cycle

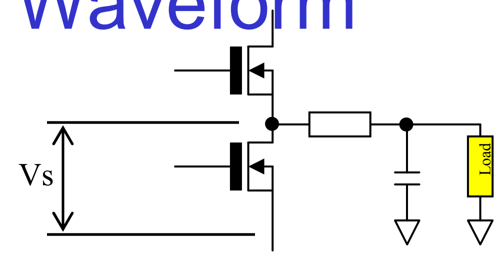


In Positive Half Cycle

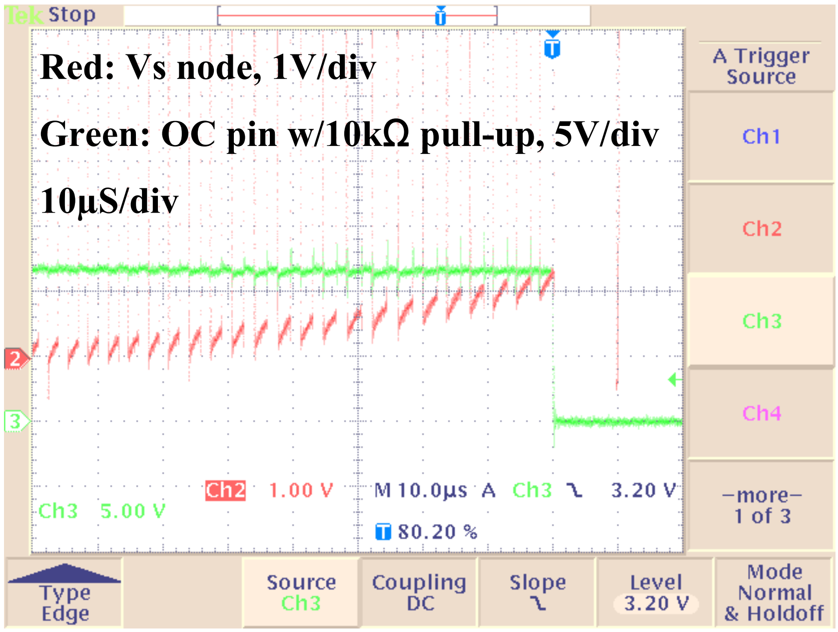


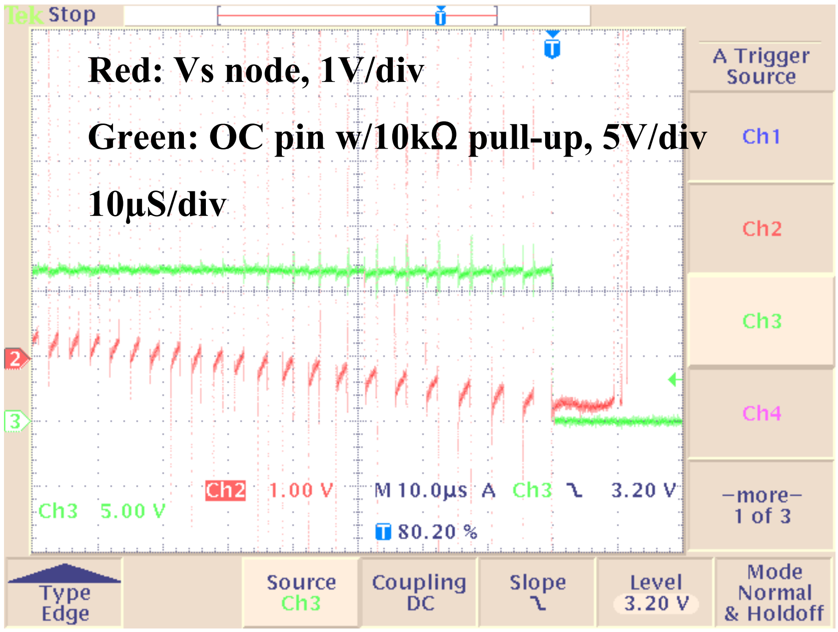
The bi-directional current sensing can capture over current conditions at either positive or negative current direction. In this demonstration, the threshold for Vs is set to be ±1V by setting OC_{SET1}=1V and OC_{SET2}=3V, which can be translated into 15A trip level with 70mΩ $R_{DS(ON)}$.

IRS20124 OC Functionality - Vs Waveform



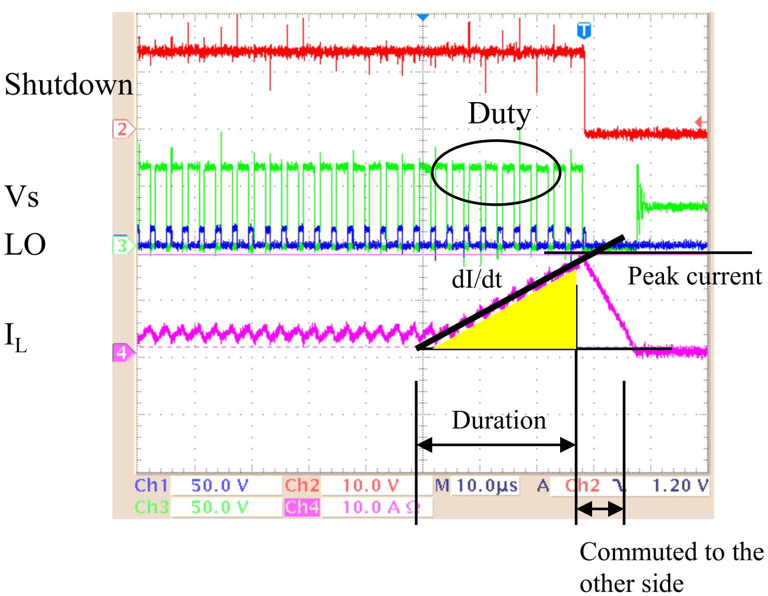
These are close up shots of overload protection with magnified waveform of Vs. At the instance voltage at Vs reaches trip level, which is ±1V in this setting, OC pin shuts down the switching and the MOSFET is protected.

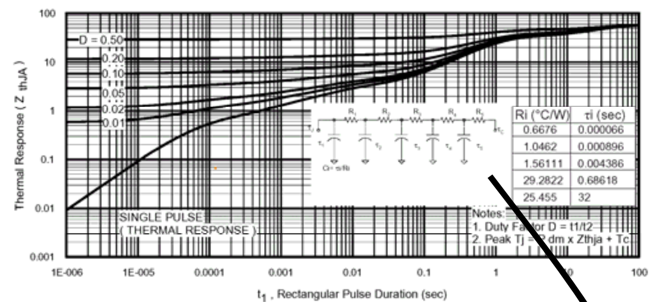




Tj Estimation in Short Circuit Event

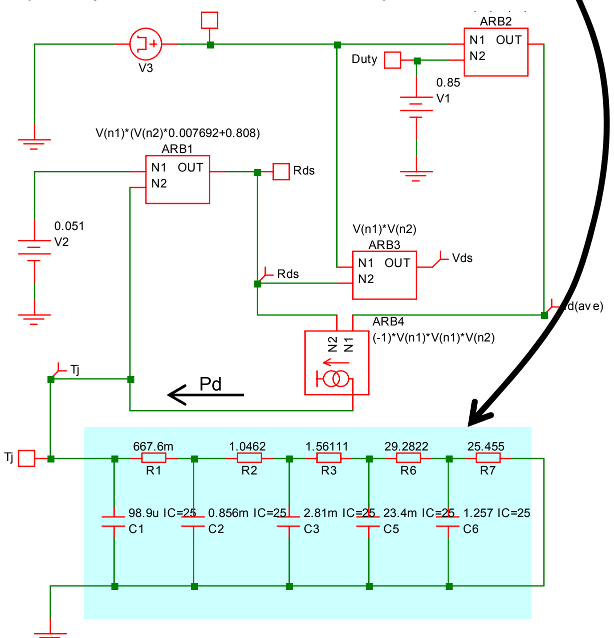
All the DIGITAL AUDIO MOSFET have thermal equivalent circuit on the datasheet for transient thermal analysis. The junction temperature of the MOSFET at the end of the over current protection event can be estimated using this model along with the waveform from the bench evaluations.





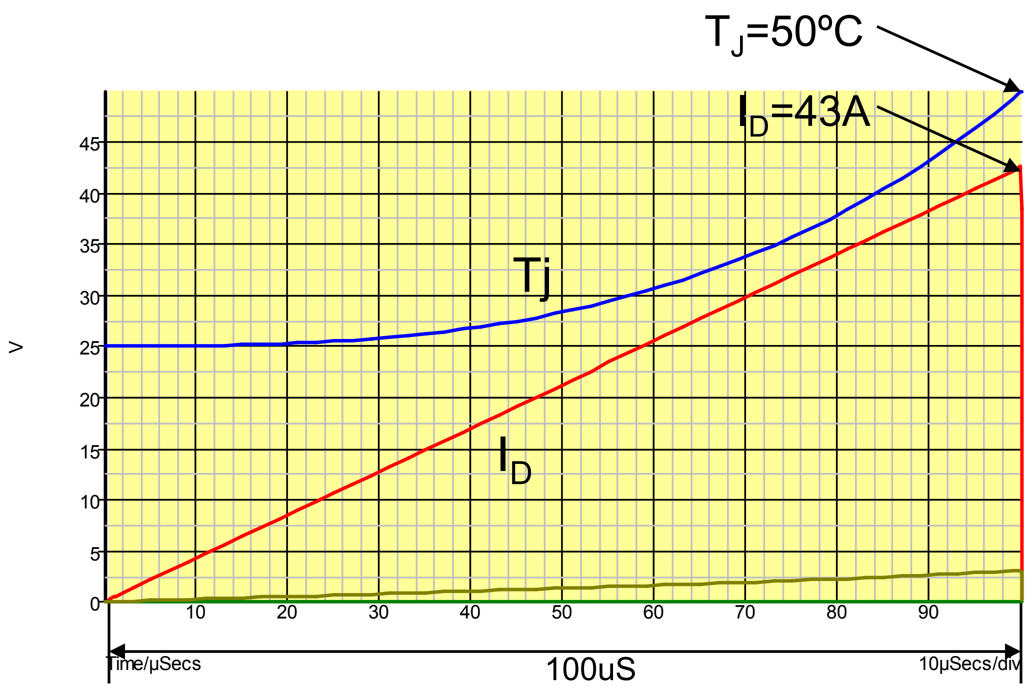
Transient Thermal Impedance

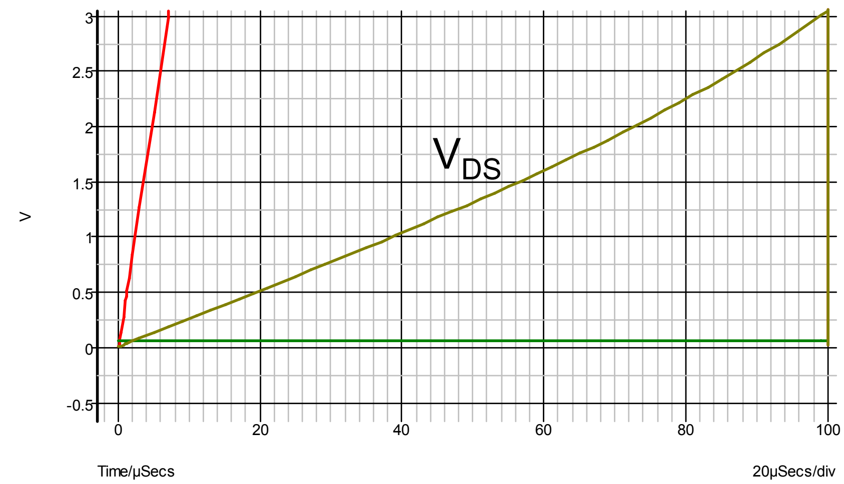
(Excerpt from IRF6665 Datasheet)

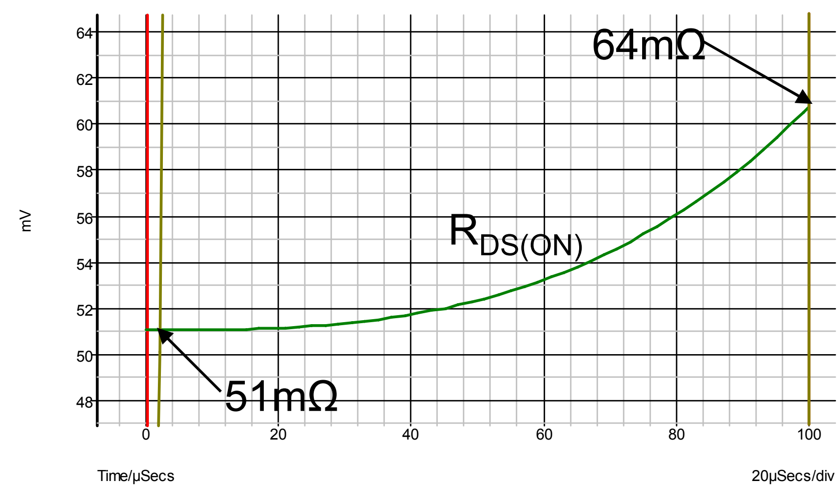


<u>An Example of Tj Simulation using a Circuit Simulator</u>

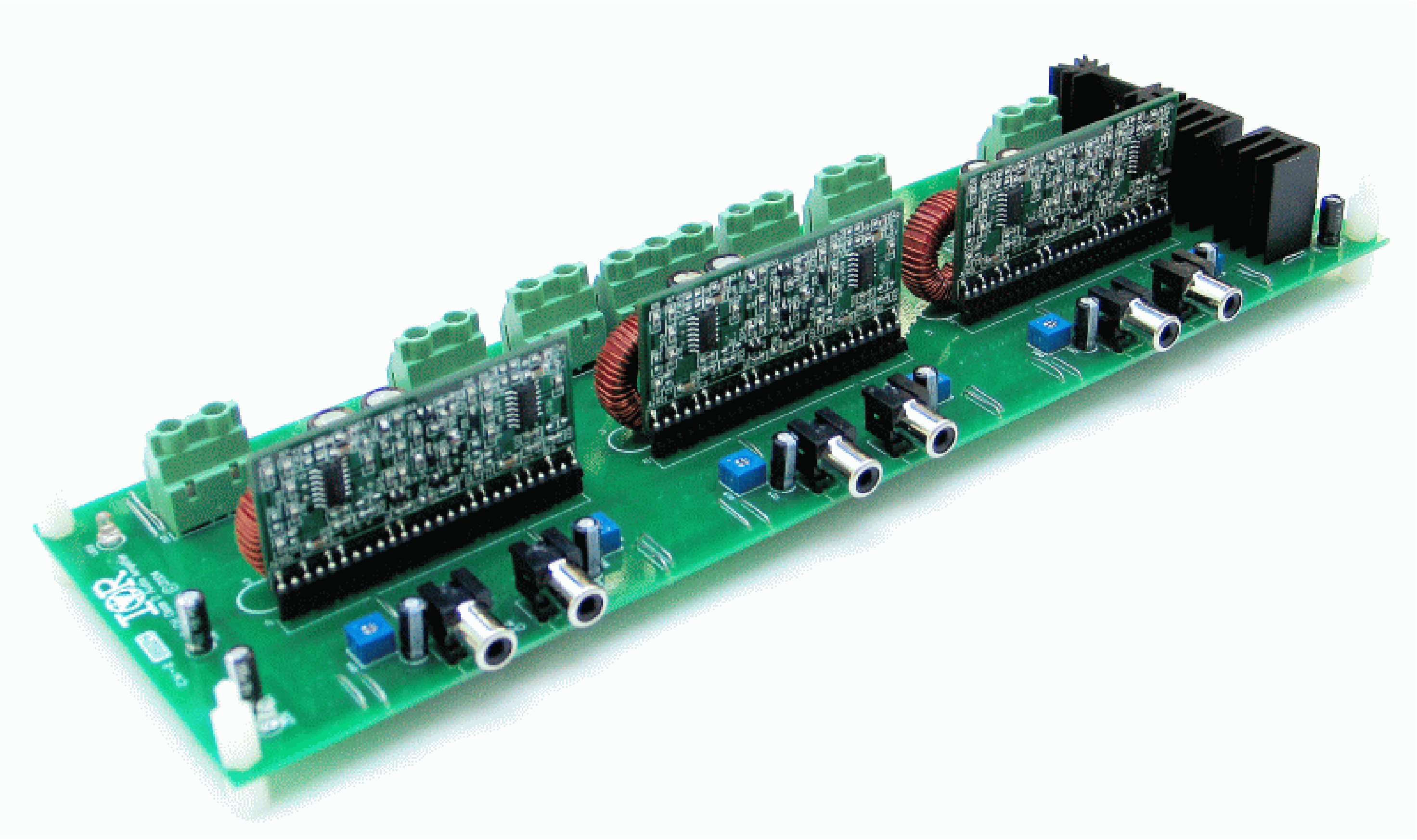
Tj Estimation Simulation Result







Chapter 4 Design Example



100W x 6 Channels Design

Specs:

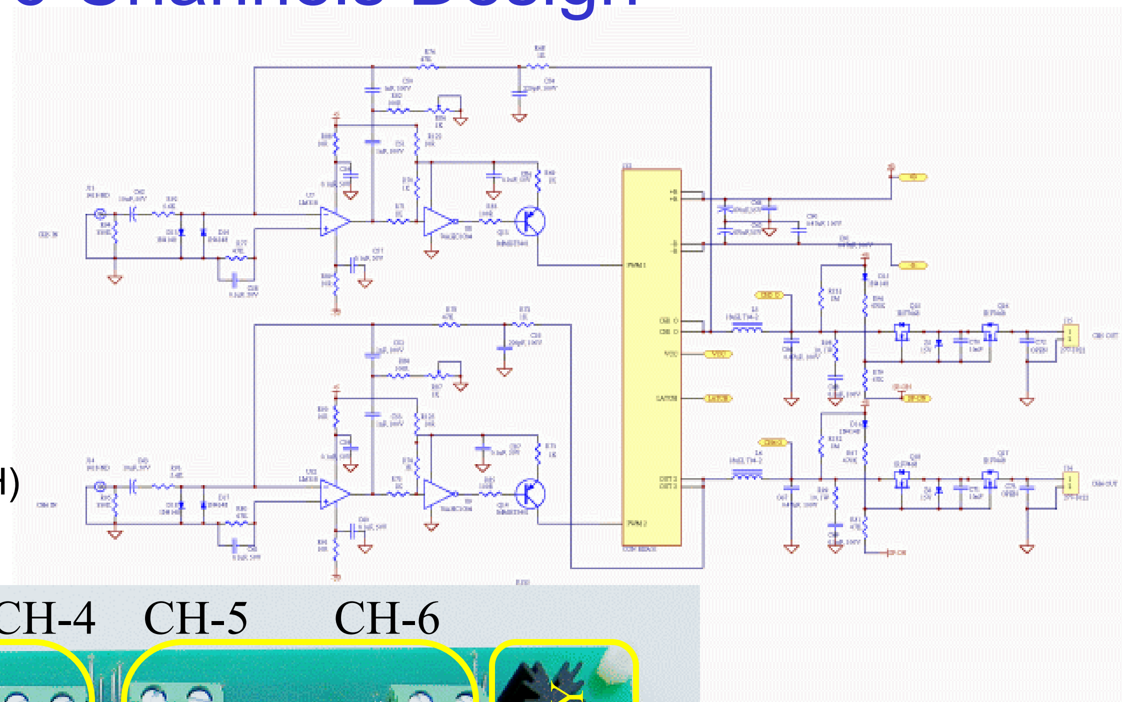
Supply Voltage: ±35V

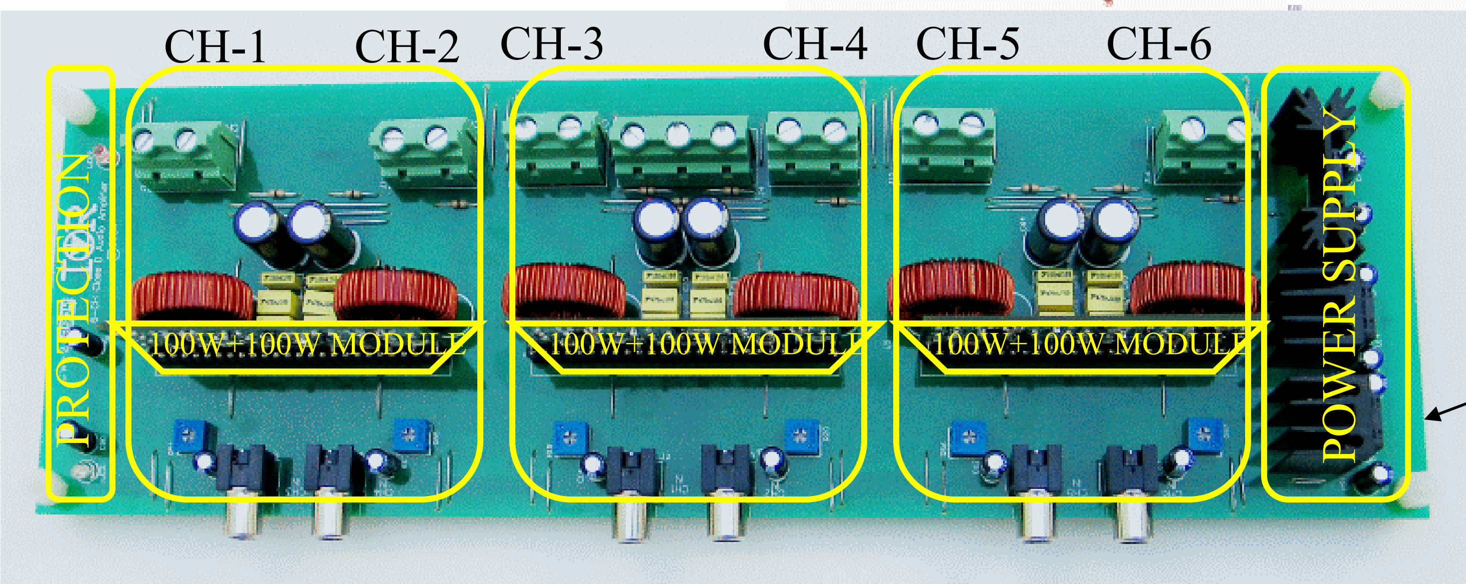
Output Power: 6ch x 100W into 8 ohm

Protections: OCP, DC, OTP, OVP

IR devices: IRS20124, IRF6665

Dimensions: 295mm x 95mm x 40mm(H)

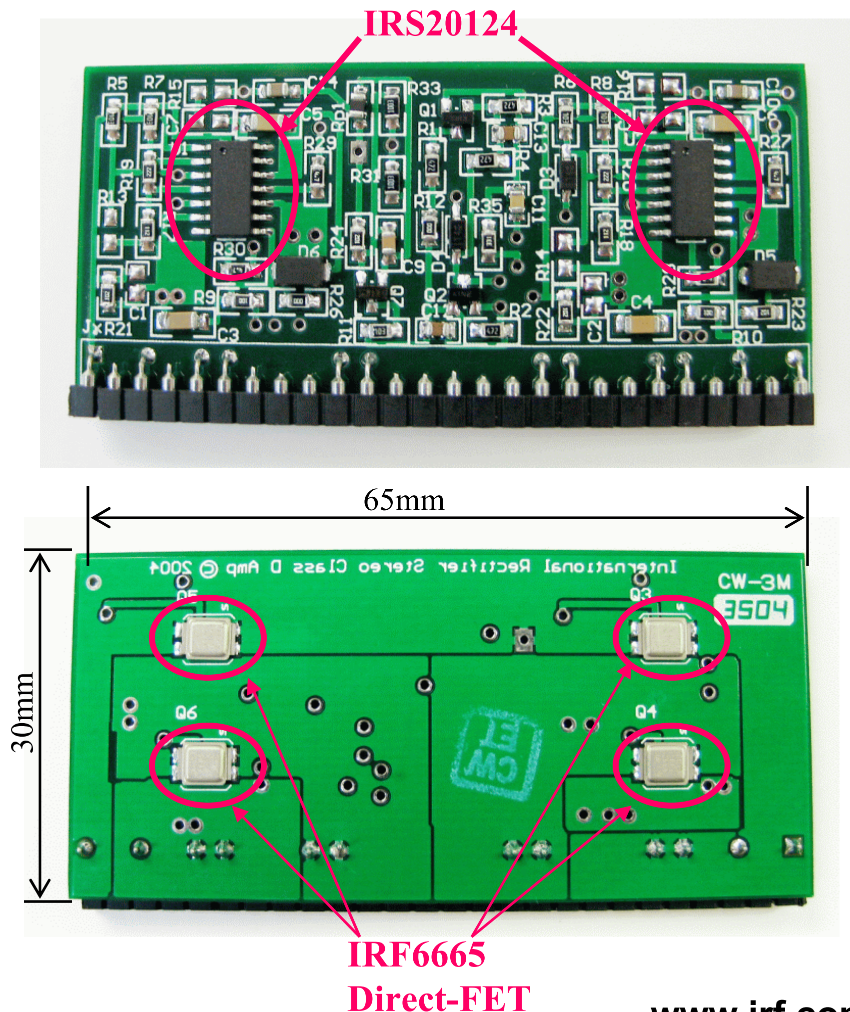




Single layer board

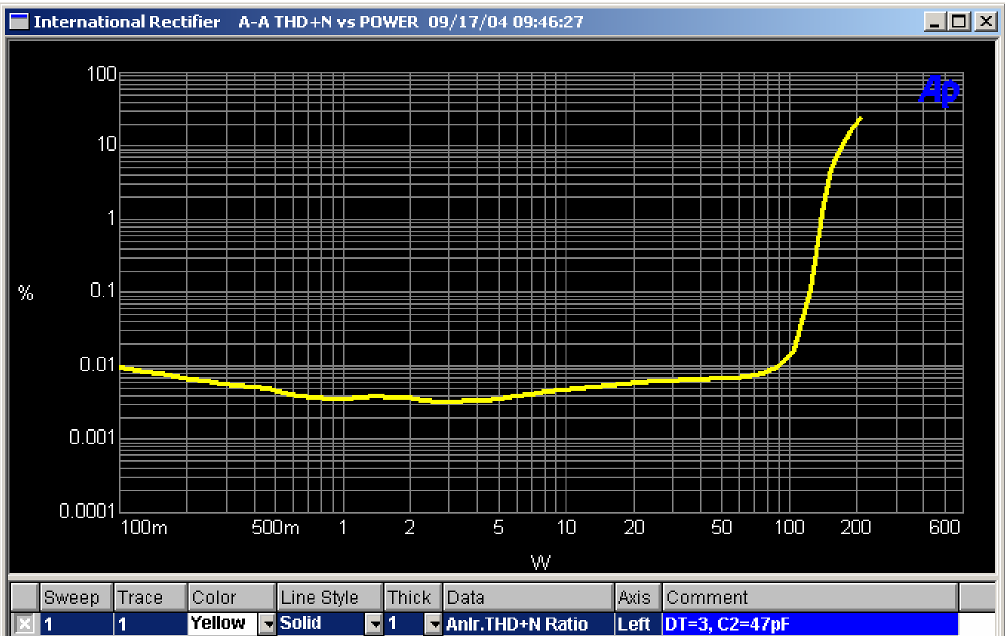
Design: 100W+100W Module

- **IR's latest technology allows continuous 100W+100W audio outputs with no heat sink attached.**
- All the critical current paths are included in the module so that a single layer PC board can be used.
- All the tricky functions, such as dead-time generation and over current protection, are included inside the module.
- Over temperature protection
- Digital Audio Direct-FET IRF6665 and Digital Audio gate driver IRS20124 placed back to back are a perfect combination to obtain minimal stray inductances.



Design Test Results

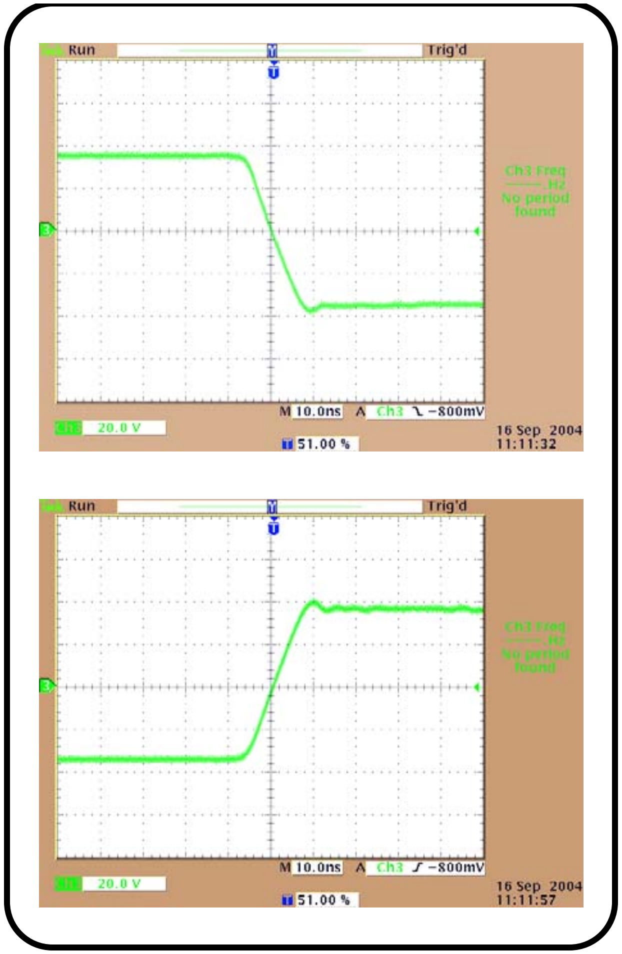
THD+N Performance, ±35.0V, 4 ohm load



120W @THD=1%
170W @THD=10%
f_{SW}=430kHz

THD=0.01%@50W
Noise=62uVrms (IHF-A)
S/N=110dB

Switching Waveforms (10nS/div, 20V/div)



Conclusion 2

By using IR's Digital Audio Gate Drivers and MOSFETs,

- **Class D audio amplifier design is no longer a do-it-by-feel trial and error process.**
- **Class D amplifier is now entering a new age of do-it-yourself design with superior efficiency, performance and ruggedness.**

Visit IR's Audio Website for more information:

http://www.irf.com/product-info/audio/