Ciclo de Palestras Sobre Controle Térmico de Satélites

Projeto Térmico de Equipamentos Eletrônicos

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Divisão de Mecânica Espacial e Controle - DMC

INPE-2004

Objetivos do projeto térmico

•Prevent catastrophic thermal failure

•Extend the useful lifetime of the electronic system

Catastrophic thermal failure is usually the result of :

- thermal fracture of a mechanical element
- separation of leads
- semiconductor material failure due to overheating
- thermo-chemical deterioration of materials

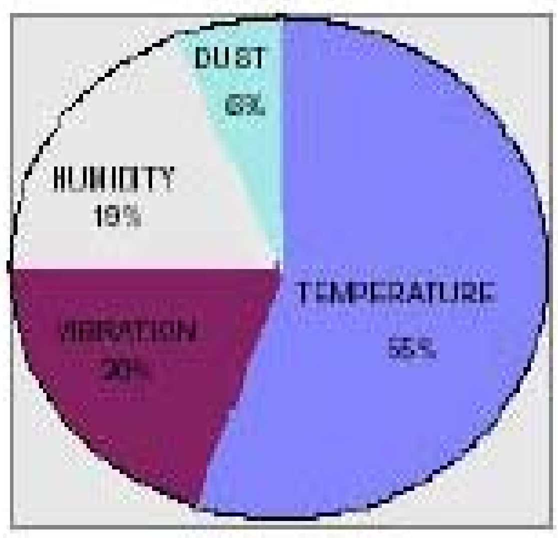
Confiabilidade e temperatura

EXAMPLE:

For silicon transistors,
failure rate increases by a
factor of 5-7 as operating
temperature is raised from 25-130 oC.

Thermal stress is introduced when
material with different
CTEs are subjected to cycling

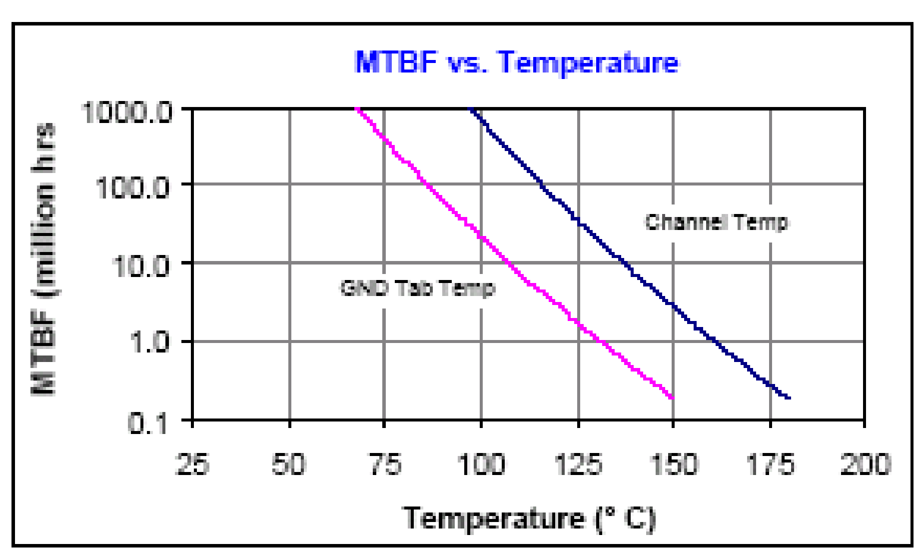
Temperature cycling above +/- 15 oC
around an average operating point also
reduces reliability



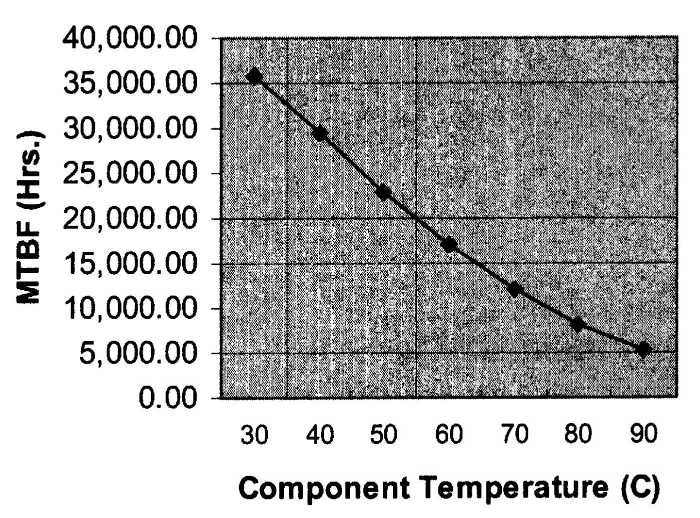
Failure rate
increases exponentially with
operating temperature

http://www.ece.gatech.edu/research/labs/vc/packaging/lectures/lecture12.pdf

Confiabilidade e temperatura: MTBF



Amplifier



Avionics

MTBF – Mean-Time-Between-Failure
MROT – Maximal-Recommended-Operating-Temperature (<~85 oC)
HTOL – High-Temperature-Operating-Lifetime (at ~125 oC)

www.wj.com/pdf/appnotes/AG101

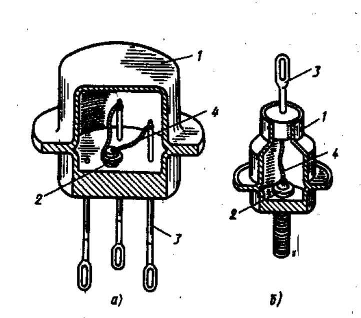
Confiabilidade e temperatura: razão de falhas HT/LT

TABLE I. Failure Rates

Part Description	λb Failures Per Million Hours. Base Failure Rate		ΔT°c	Ratio of High to Low Failure Rate
	High Temperature	Low Temperature		
PNP Silicon Transistors	.063 at 130°c and 0.3 stress	.0096 at 25°c and 0.3 stress	105	7:1
NPN Silicon Transistors	.033 at 130°c and 0.3 stress	.0064 at 25°c and 0.3 stress	105	5:1
Glass Capacitors	.047 at 120°c and 0.5 stress	.001 at 25°c and 0.5 stress	95	47:1
Transformers and Coils MIL-T-27 Class Q	.0267 at 85°c	.0008 at 25°c	60	33:1
Resistors Carbon Comp	.0065 at 100°c and 0.5 stress	.0003 at 25°c and 0.5 stress	75	22:1

MIL-HDBK-251

Componentes eletrônicos



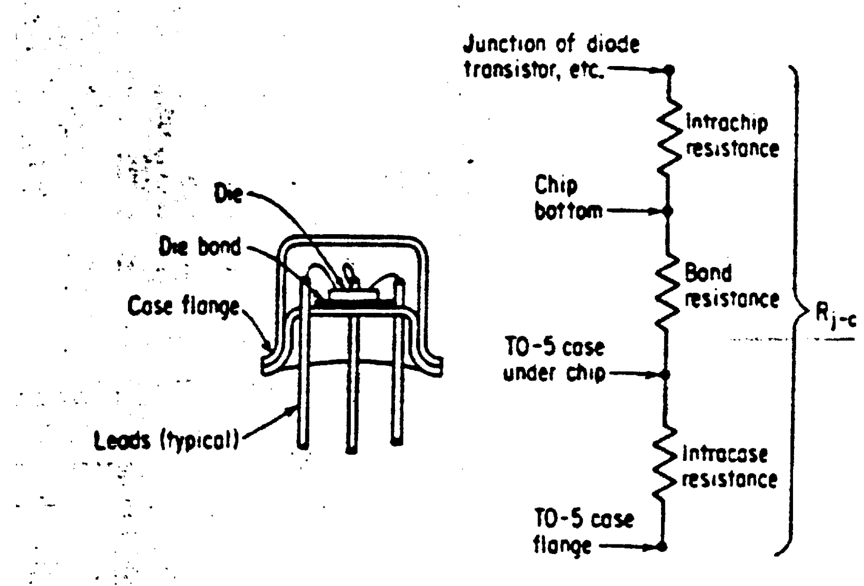
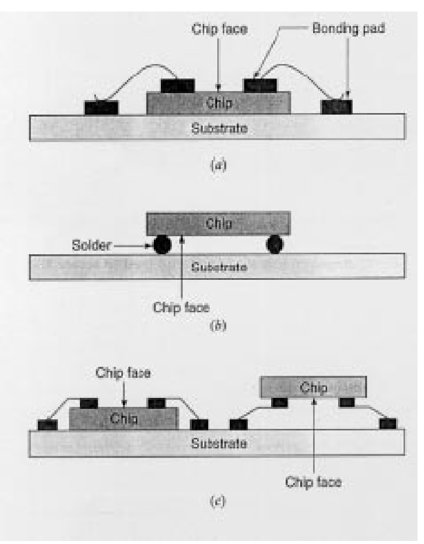


FIG. 12. Composite thermal-resistance paths for TO-5 package.



Semiconductors: germanium –> 100...110 oC
Semiconductors: silicon –> 125..200 oC
Resistors -> 70...150 oC
Transformers -> 90....180 oC
Capacitors -> 40...150 oC

-0.

Componentes eletrônicos: chips

Table 1.1 Characteristics of Single Chip Packages

I. SURFACE MOUNTED		SHAPE	TYPICAL FEATURES		
			MATERIAL	LEAD PITCH	# OF I/O PINS
SOP	SMALL OUTLINE PACKAGE		PLASTIC	•1.27mm (50MIL) •2 direction lead	8-40
QFP	QUAD FLAT PACKAGE		PLASTIC	• 1.0mm •0.8mm •0.65mm •4 direction lead	88-200
FPG	FLAT PACKAGE OF GLASS		CERAMIC	•1.27mm (50MIL) •.762mm (30MIL) •2 direction lead •4 direction lead	20-80
LCC	LEADLESS CHIP CARRIER		CERAMIC	•1.27mm (50MIL) •1.016mm(40MIL) •.762mm (30MIL)	20-40
PLCC	PLASTIC LEADED CHIP CARRIER		PLASTIC	•1.27mm (50MIL) •J-shaped bend •4 direction lead	18-124
VSQF	VERY SMALL QUAD FLAT PACKAGE		PLASTIC	•0.5mm	32-100

Table 1.1 Continued

II. THROUGH HOLE MOUNTED		SHAPE	TYPICAL FEATURES		
			MATERIAL	LEAD PITCH	# OF I/O PINS
DIP	DUAL INLINE PACKAGE		CERAMIC PLASTIC	•2.54mm(100MIL)	8-64
SIP	SINGLE INLINE PACKAGE		PLASTIC	•2.54mm(100MIL) •1 direction lead	3-25
ZIP	ZIGZAG INLINE PACKAGE		PLASTIC	•2.54mm(100MIL) •1 direction lead	16-24
S-DIP	SHRINK DIP		PLASTIC	•1.778mm(70MIL)	20-64
SK-DIP	SKINNY DIP		CERAMIC PLASTIC	•2.54mm •Half-size pitch in the width direction	24-32
PGA	PIN GRID ARRAY		CERAMIC PLASTIC	•2.54mm(100MIL)	

Data obtained from [Seraphim et al. (1989)] and [Tummala and Rymaszewski (1989)].

Advances in thermal modeling of electronic components ..ISBN 0-7918-0018-0.

Componentes eletrônicos: tendências a "multi-chips"

Smaller Size

SOP

SOJ

S-SOP

TSOP

QFJ (PLCC)

Fine Pitch Bonding

TQFP

QFP

TAB

Higher Pin Count

Smaller Size, Weight

PIH 1000

BGA

CSP

MCM

DIP/PGA

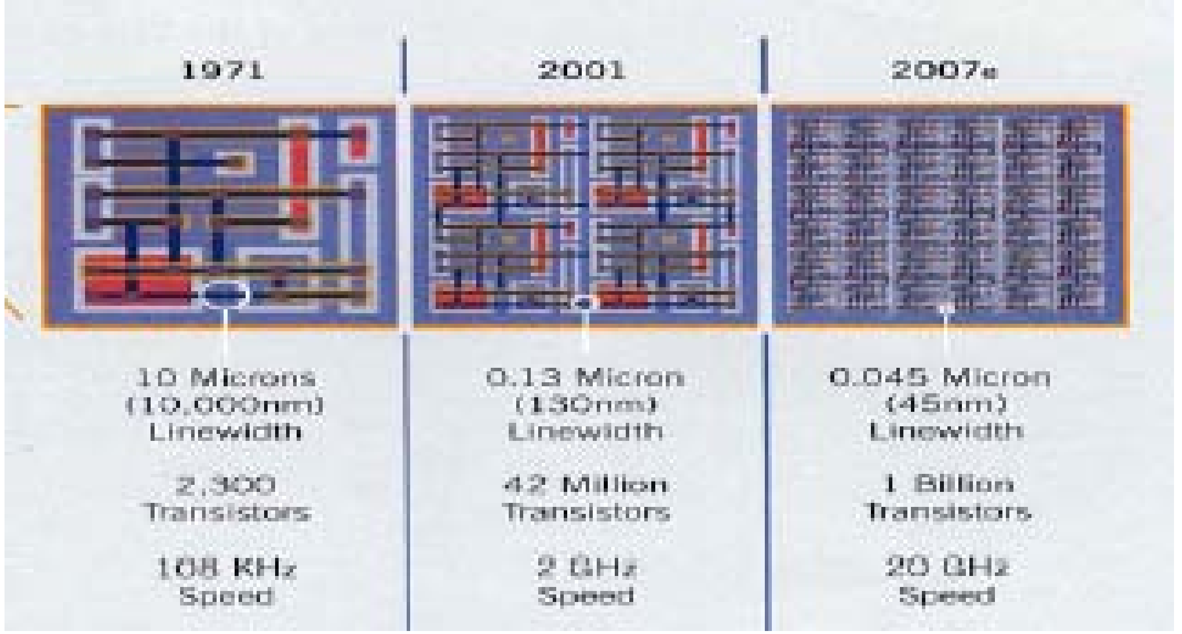
SLIM 2000-2010

Year 1970s 1980s 1990s

Figure 1-35. Single-Chip Package Evolution Leading to Multichip Packaging

Microelectronics packaging Handbook: Charman & Hall, 1997.

Evolução do micro-chip



calce Advanced liquid Cooling, Scottsdale's, AZ, , May 13-2003

Tendências de fluxo de calor

High-Performance Chip Power

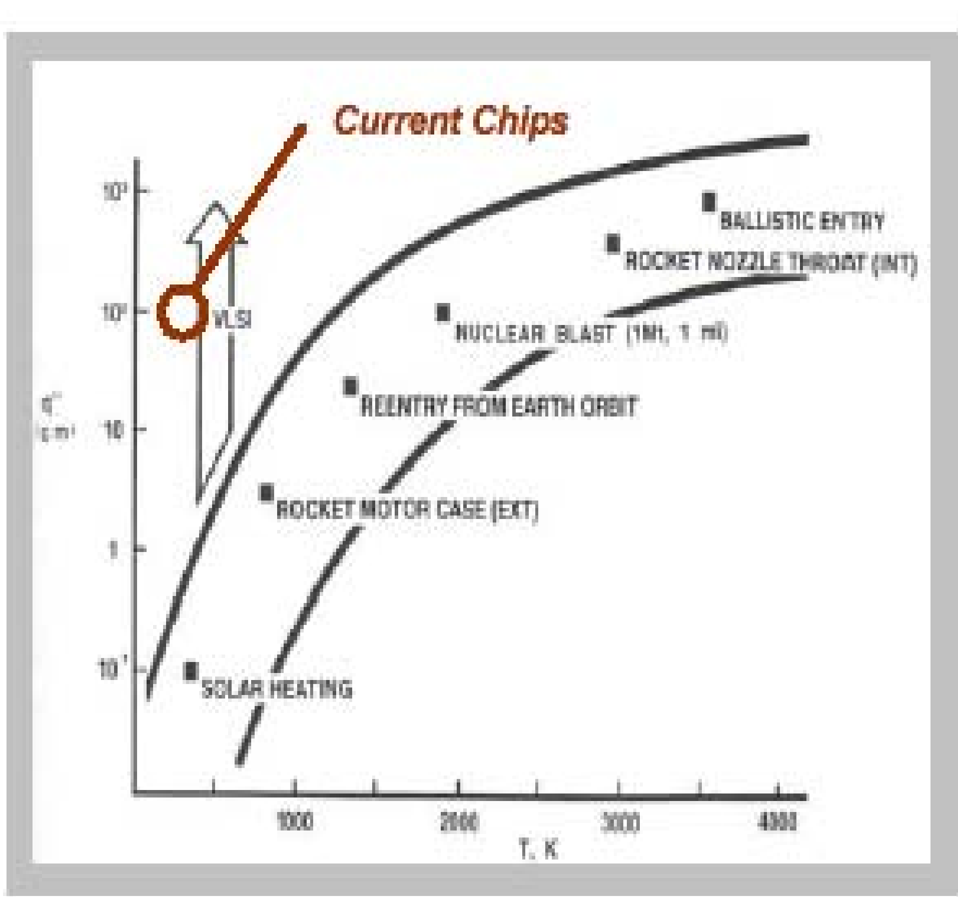
Chip Power Dissipation (Watts)
300
250
200
150
100
50
Maximum
Minimum
2001 2003 2005 2007 2009
Year

calce Advanced liquid Cooling, Scottsdale's, AZ, , May 13-2003

X86 power dissipation
Chip Power (W)
100 90 80 70 60 50 40 30 20 10 0
486
Pentium
Pentium 3
Pentium 4
Year of Introduction

http://web.mit.edu/hmtl/www/papers/HANNEMANN.pdf

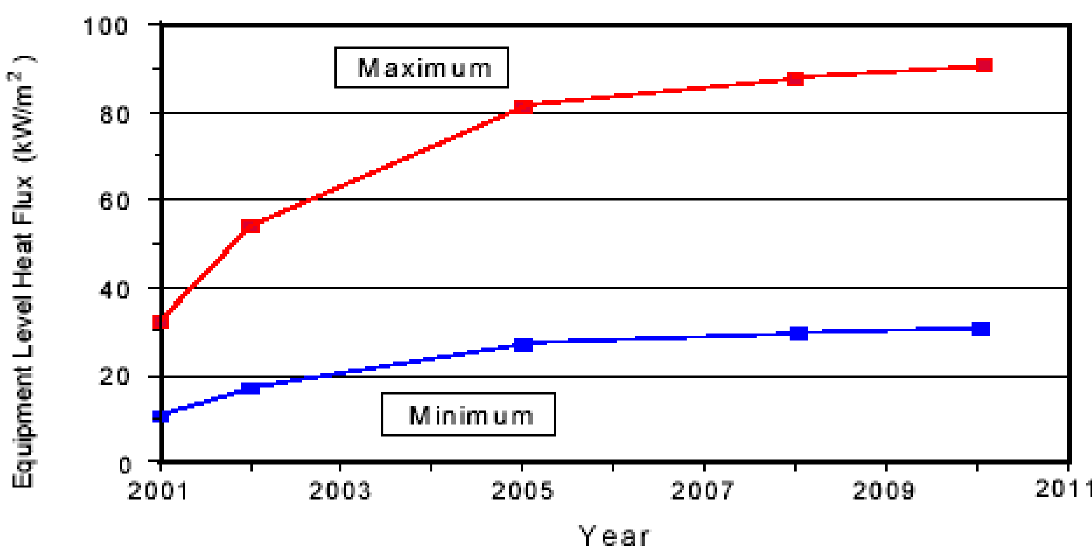
Densidade de fluxo



While absolute power levels in microelectronic devices are relatively modest (~1..~100 W), heat fluxes can be significant (~50 W/cm2 in current electronic chips; up to 2000 W/cm2 in semiconductor lasers).
Further, temperatures at the chip surface must be kept to rather low levels (~100 C) for both performance and reliability reasons.

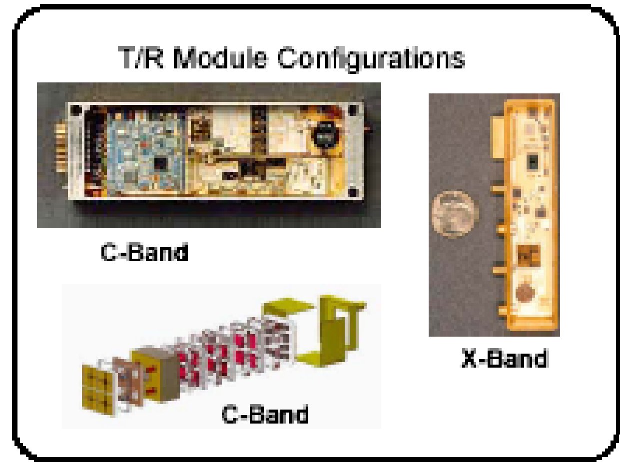
http://web.mit.edu/hmtl/www/papers/HANNEMANN.pdf

Densidade de fluxo



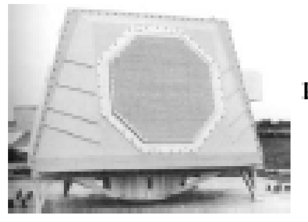
http://web.mit.edu/hmtl/www/papers/HANNEMANN.pdf

Densidade de fluxo

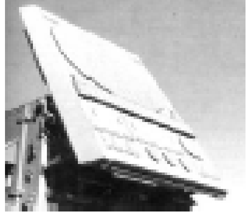


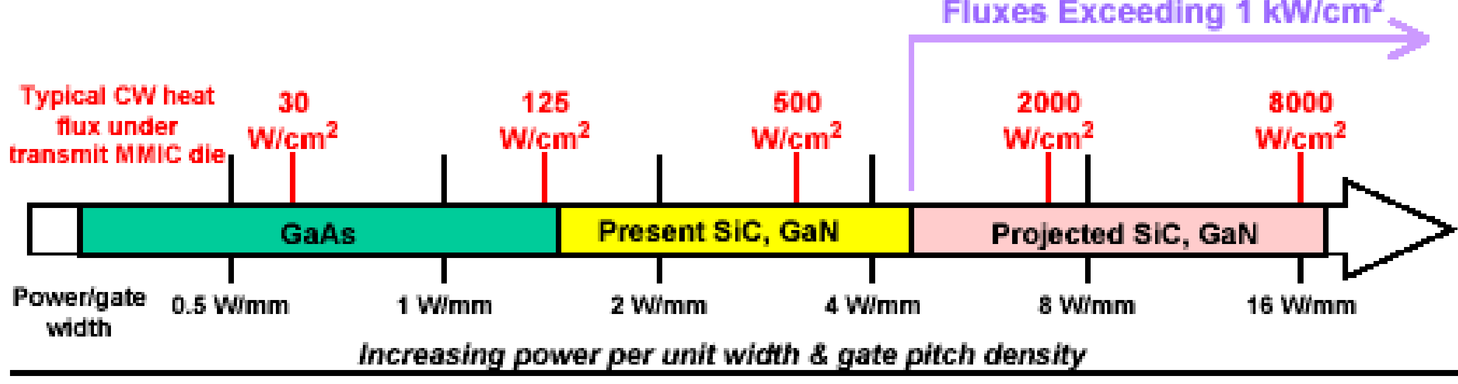
S-band ~ 5 × 5 cm; C-band ~ 3 × 3 cm

X-band ~ 1.5 × 1.5 cm



Phased Arrays





calce Advanced liquid Cooling, Scottsdale's, AZ, , May 13-2003 14

University of Maryland

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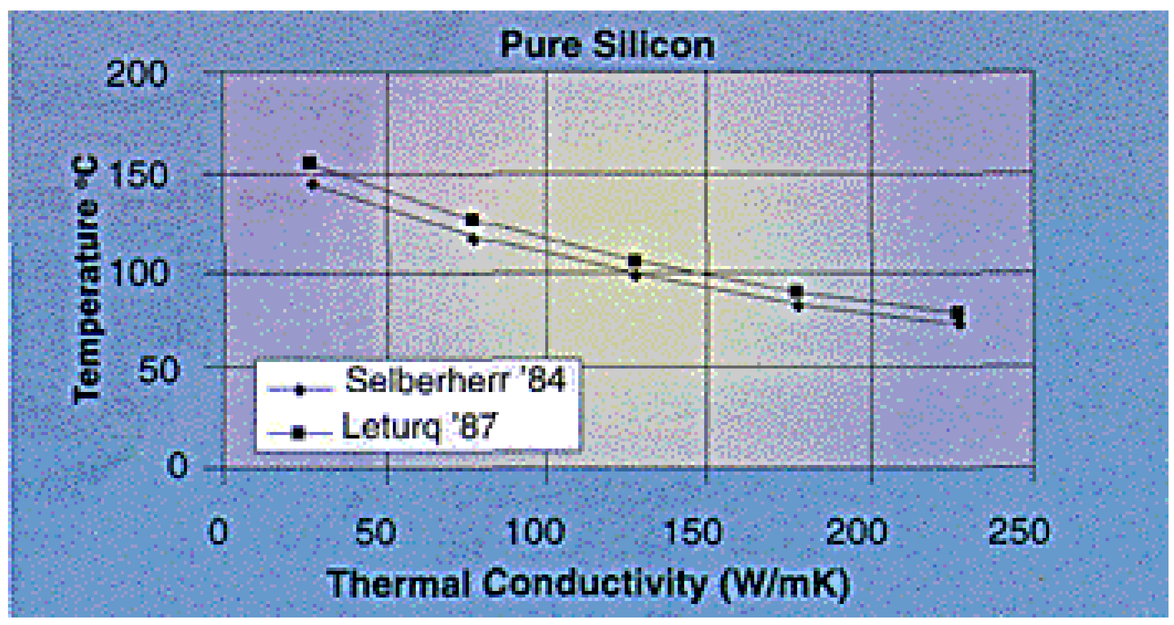
Materiais de “packaging”

Table 4-2. Thermal Conductivity of Packaging Materials at 25°C

	W/m K		W/m K
Aluminum (pure)	216	Molybdenum	138
Alumina	25	Mylar	0.2
Bakelite	0.2	Nickel	92
Beryllia	230	Nylon	0.2
Copper	398	Platinum	69
Diamond	2300	Quartz	1.0
Epoxy (no fill)	0.2	Silicon (undoped)	144
Epoxy (high fill)	2.1	Silicone grease	0.2
Glass–epoxy	1.7	Silicone rubber	0.2
Gold	297	Silver	418
Kovar	16.4	Solder (95% Pb, 5% Sn)	36
Lead	34	Teflon	0.2
Magnesium (cast)	70	Thermal grease/paste	≈ 1
Mica	0.5	Tin	63

Microelectronics packaging Handbook: Charman & Hall, 1997

Propriedade do silicone



$$k = 1.5\,(T/300)^{-4/3}$$

Electronic cooling: technical data

Propriedade da cerâmica

		Thermal Conductivity (W/mK) at 20° C
AIN	Aluminum Nitride	80-200, 180, 260
$A1_20_3$	Aluminum Oxide	18-36
BeO	Beryllium Oxide	184, 200, 220, 242, 250, 300
BN	Boron Nitride	15-40, 250-300, 600
SiC	Silicon Carbide	90-160, 70-200, 80, 210

Ceramics are increasingly used in packages and printed circuit boards, because they have a number of advantages over plastics: much higher thermal conductivity, possible match of the coefficient of thermal expansion, and hermetic sealing.

“Electronic cooling”: technical data

Condutividade dos multi-chips

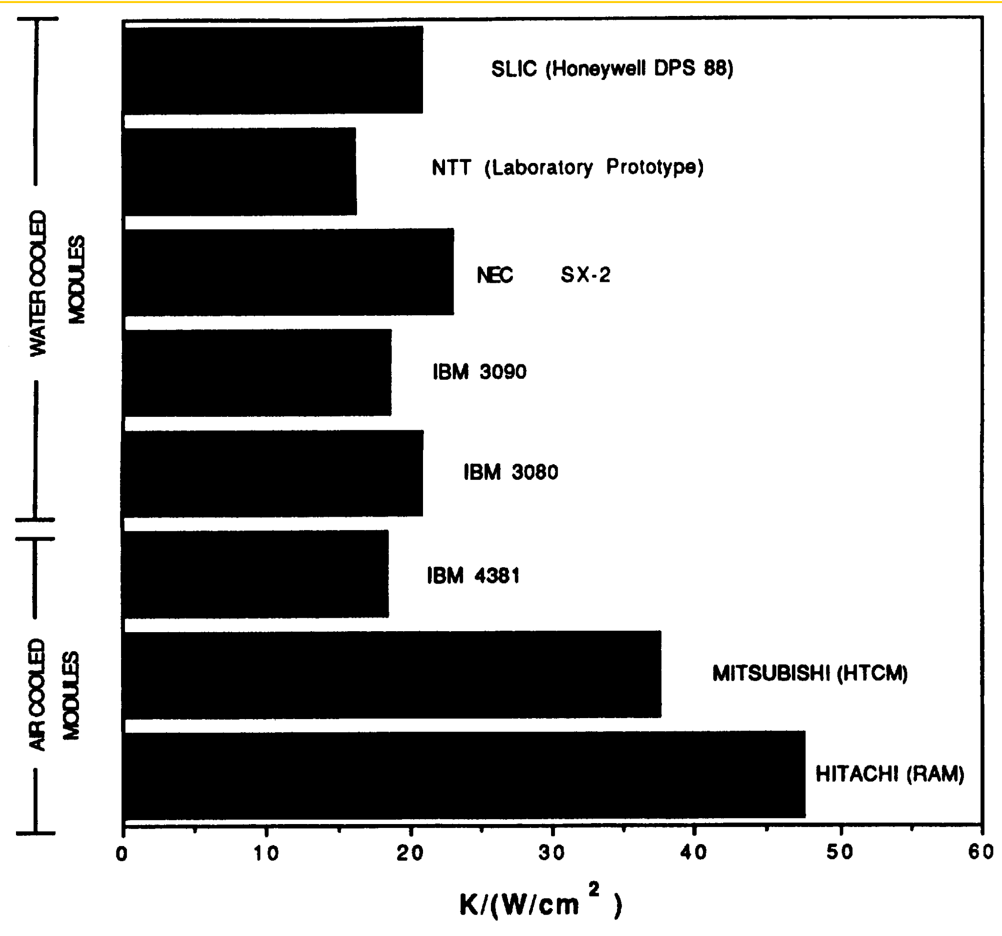


Figure 1.17 Specific thermal resistances for multichip modules [Bar-Cohen (1988)].

Advances in thermal modeling of electronic components .
.ISBN 0-7918-0018-0.

“Spreaders” (“Doublers”)

Distributes heat evenly in two dimensions, eliminating "hot spots" while simultaneously reducing touch temperature in the third dimension.

A thermal solution that can be combined with plastics, metals or elastomers in the finished components as well as with other interface materials (fillers) to improve contact resistance

http://www.graftech.com

Materiais para "Spreaders"

Thermal Performance (°C/W)

6.00
5.00
4.00
3.00
2.00
1.00
0.00

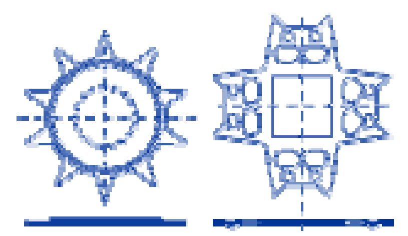
5.14 Sil-Pad 400 .007
2.45 Sil-Pad 800
2.90 Sil-Pad 900S
2.68 Sil-Pad 1500
2.21 Sil-Pad A1500
2.01 Sil-Pad 2000 .015
3.13 K-4
2.76 K-6
2.01 K-10
1.23 Q2
1.76 Q3

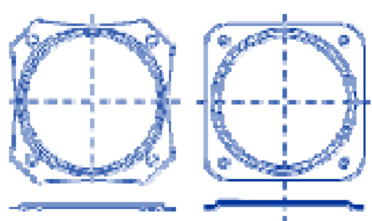
Bergquist Materials

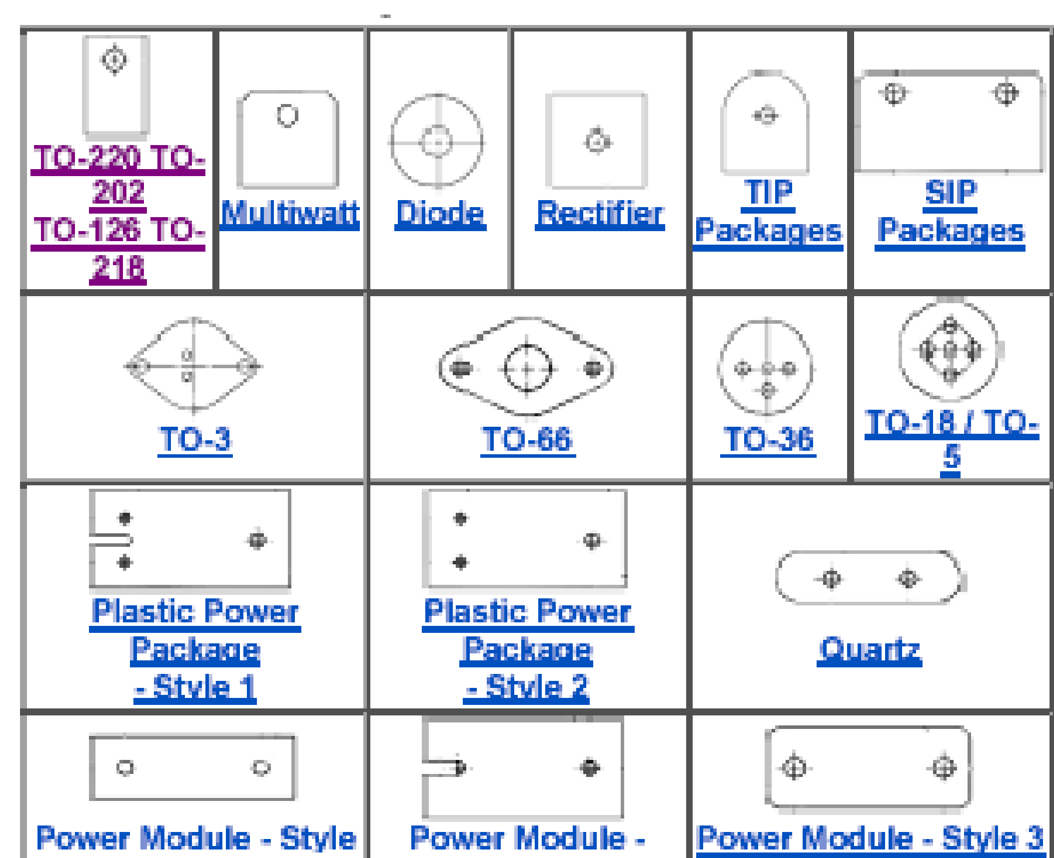
Heat Sink
Thermally Conductive Material
Device
Heat

www.bergquistcompany.com

“Pre-cut spreaders”







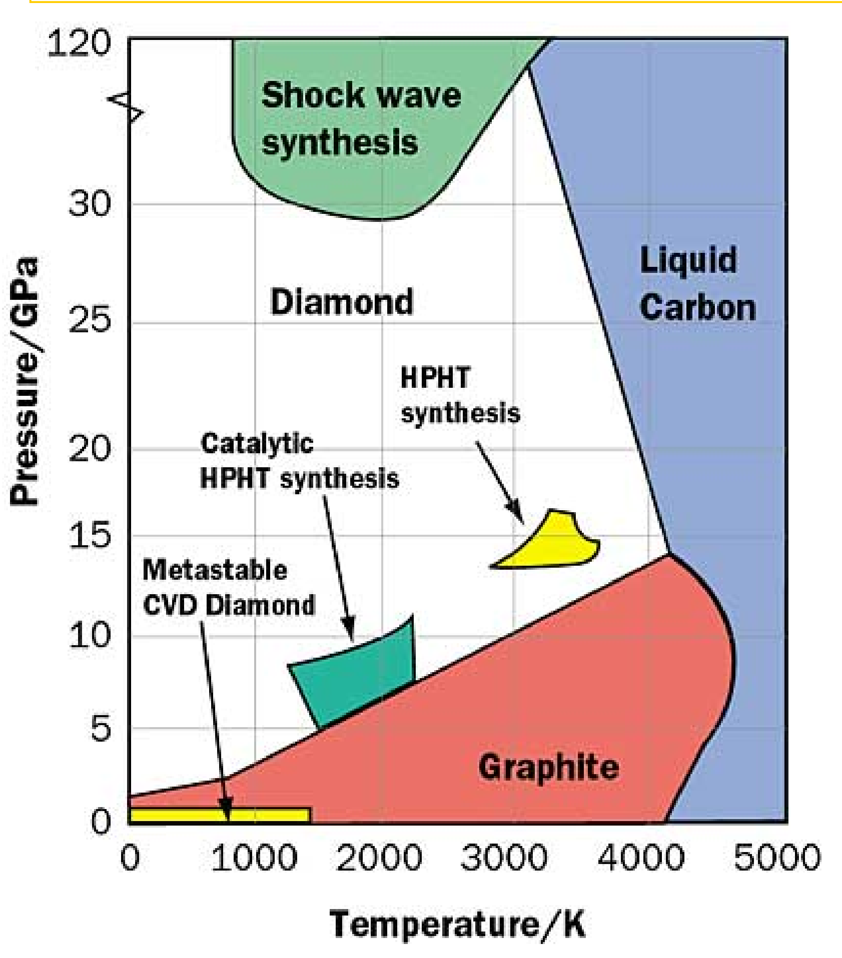
www.thermaflo.com; www.moxel.com/therm_spreaders.htm

“Lid-spreaders”

Figure 5. Achieving effective heat spreading with advanced lid designs

www.thermacore.com

Diamante e grafite

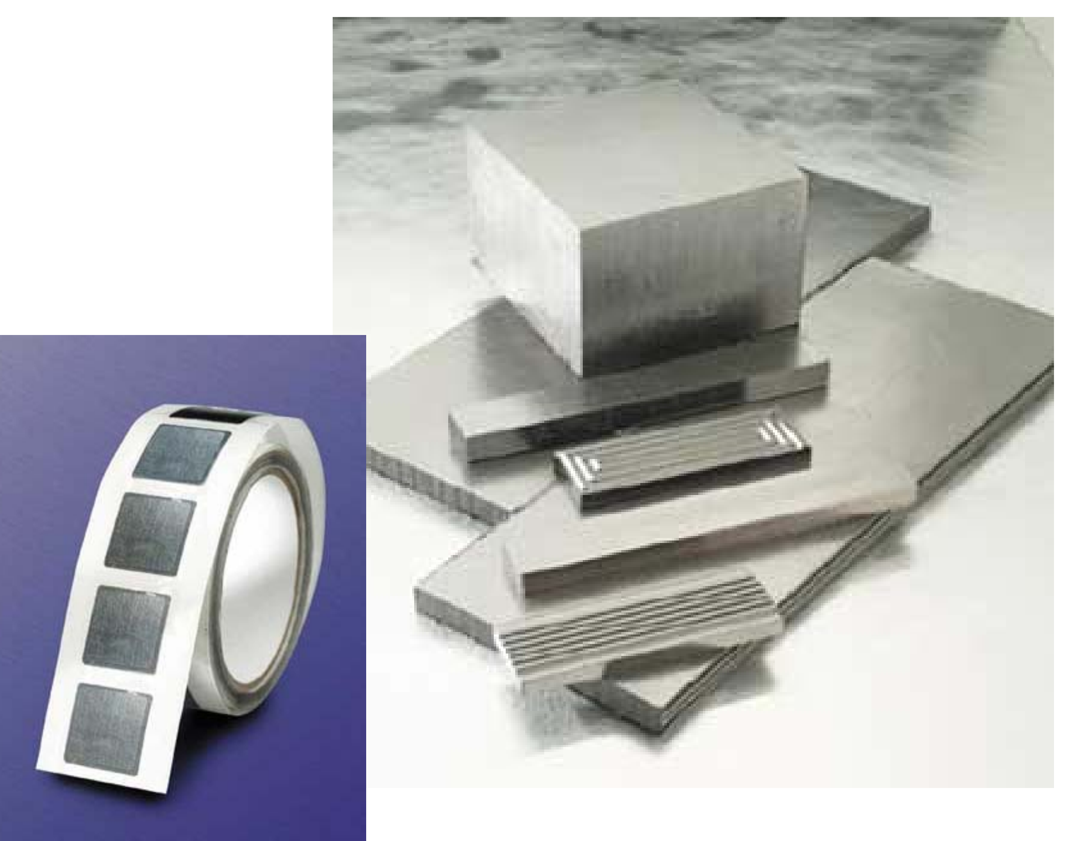


Processed natural graphite,
Pyrolytic graphite,
Graphite fiber reinforced carbon,
Polymer matrix composites,
Graphite foams,
Diamond-like carbon,
Synthetic diamond,

"Electronic cooling": technical data
http://www.bristol.ac.uk/Depts/Chemistry/MOTM/diamond/cphased.gif

HPHT – High Pressure High Temperature
CVD - Chemical Vapor Deposition

Grafite



Graphite heat spreader components.

As with thermal interface materials, the thermal anisotropy can be varied. Thermal conductivity values of 400 W/mK and 7 W/mK have been measured for in-plane and through thickness directions, respectively. The density of the components varies in the range of ~1.3-2.0 g/cm^3.
By comparison, aluminum 6061 has a density of 2.7 g/cm^3 and a thermal conductivity of ~180 W/mK, and copper has a density of 8.96 g/cm^3 and a thermal conductivity of ~400 W/mK. The material, therefore, matches the thermal performance of copper in two directions, at 15-22% of the weight.

"Electronic cooling": technical data

Compósitos com grafite

A graphite based thermal solution that can be combined with plastics, metals or elastomers in the finished components.

Custom designed thermal properties, tailorable up to 500 W/mK, and form factors to meet your needs

http://www.graftech.com

Compósitos com grafite

Composite	Source	Thermal Conductivity (W/mK) at 20°C	
		X,Y direction	Z direction
TPG Graphite Fiber	Adv. Ceramics	1700	25
Polymer / TPG	Adv. Ceramics	1180	
Cu / TPG	Adv. Ceramics	1140	
K1100 Graphite Fiber	Amoco	1100	
Thermalgraph 8000	Amoco	700	20
20 Cu / 80Thermalgraph	Amoco	892	
K1100 / Epoxy	Amoco	595	1
K1100 / Cu	Amoco	709	135

"Electronic cooling": The thermal conductivity of composite materials

"Spreaders" bifásicos: tubos de calor

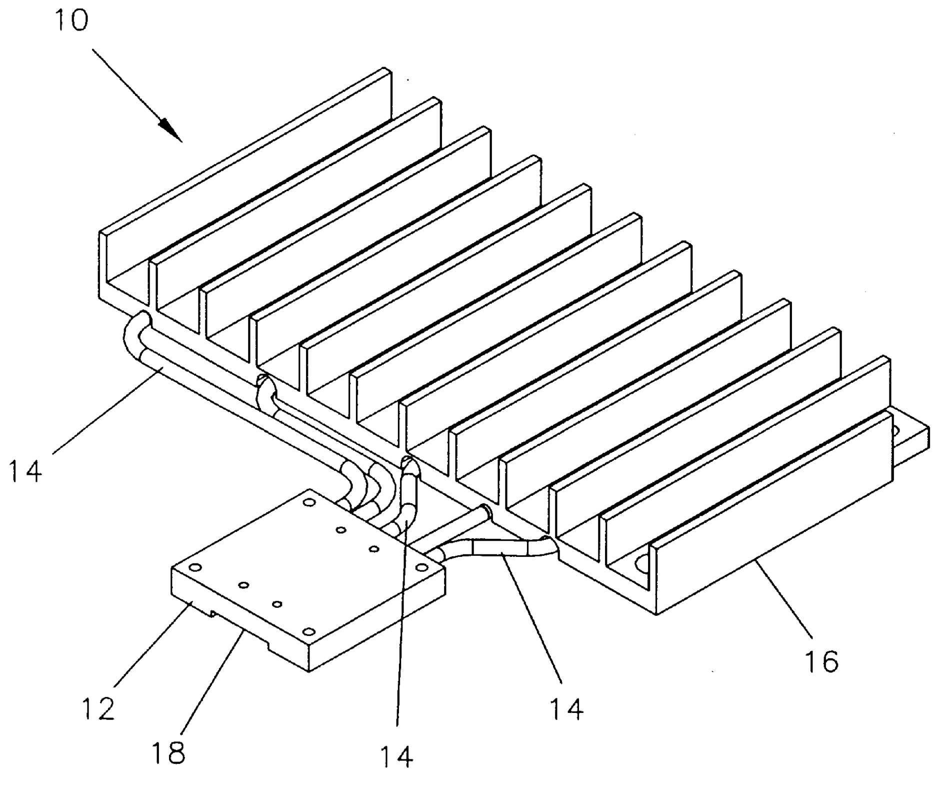


FIG. 1

"United States Patent 6,191,946

“Spreaders” bifásicos: micro-tubos de calor

10

FIG 1

20

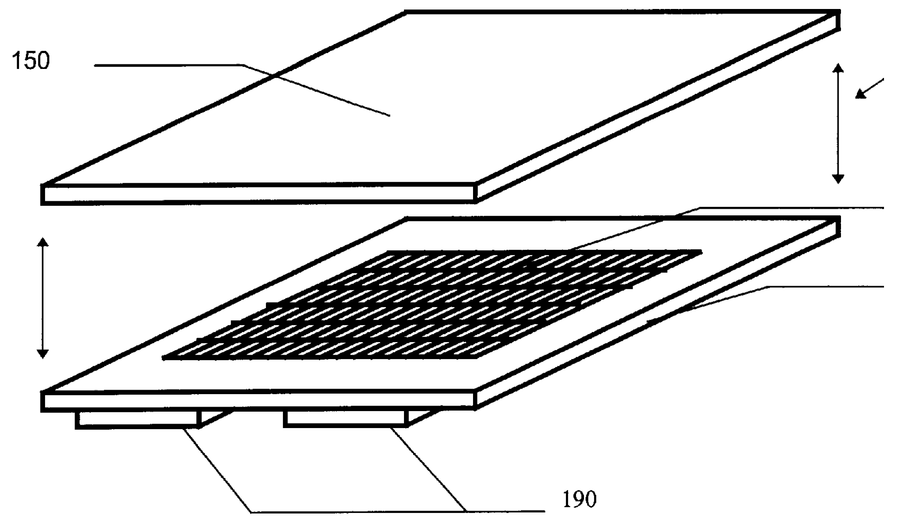
15

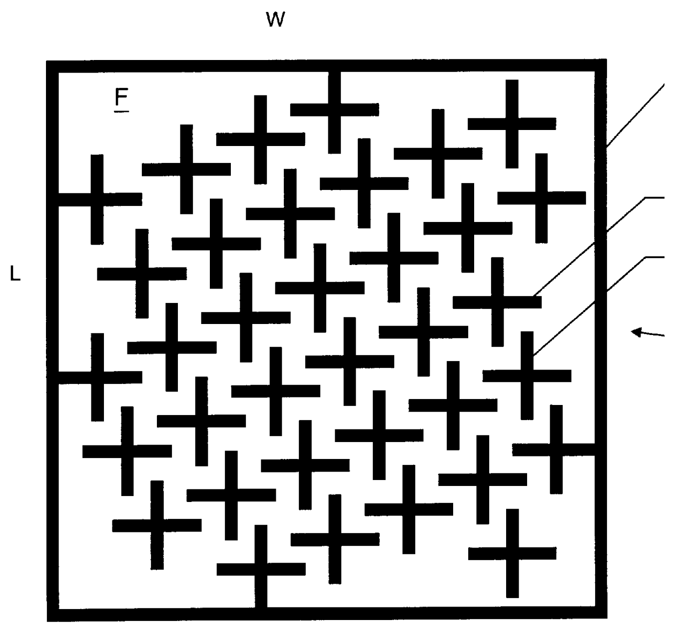
FIG 2

30

United States Patent 5,598,632

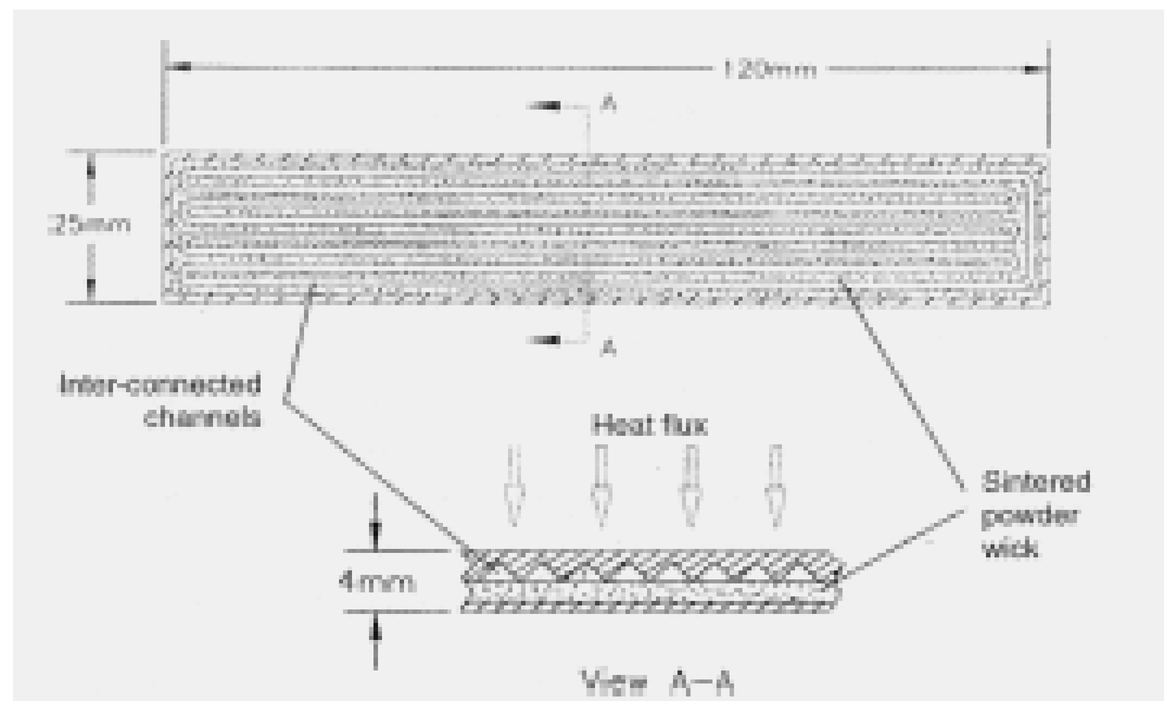
“Spreaders” bifásicos: tubo de calor plano





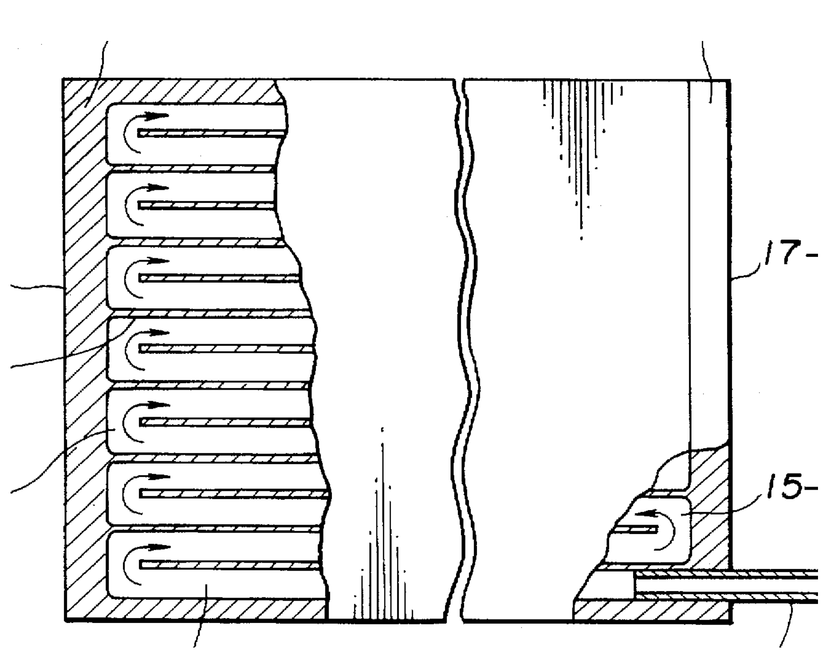
United States Patent 5,947,193

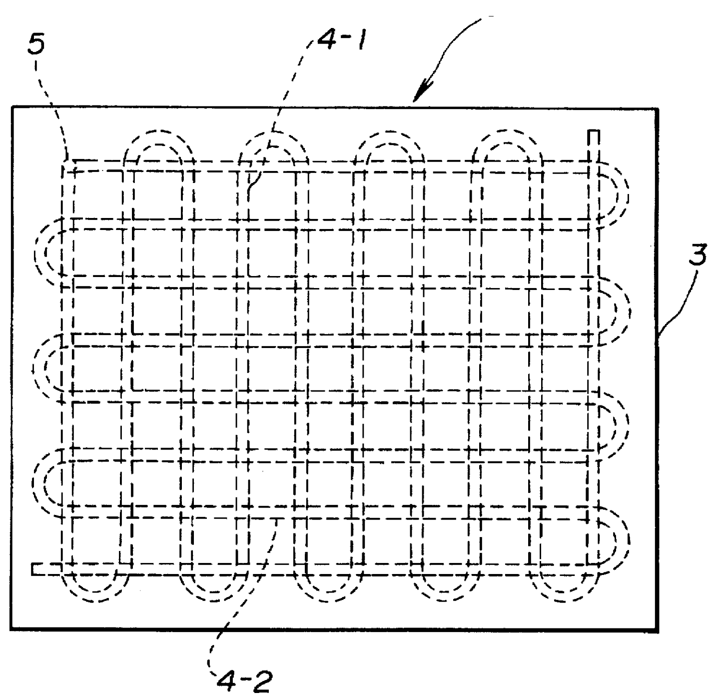
“Spreaders” bifásicos: tubo pulsativo



“COMBINED PULSATING AND CAPILLARY HEAT PIPE MECHANISM FOR COOLING OF HIGH HEAT FLUX ELECTRONICS”, by Thermacore

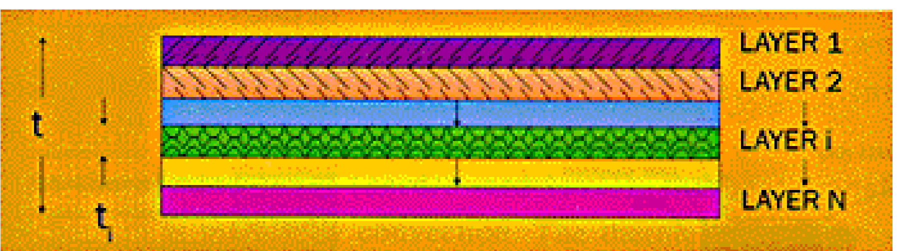
“Spreaders” bifásicos: tubo pulsativo





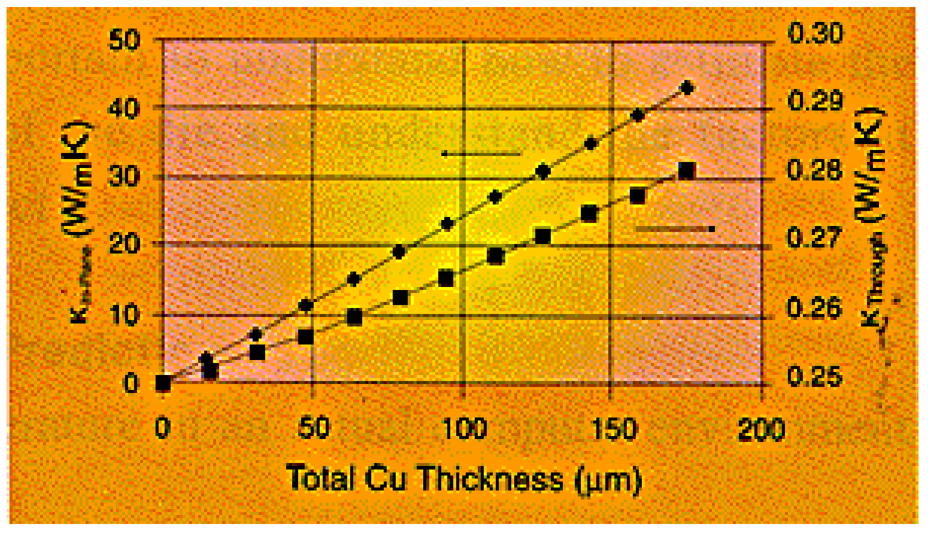
United States Patent 5,697,428

Condutividade efetivo



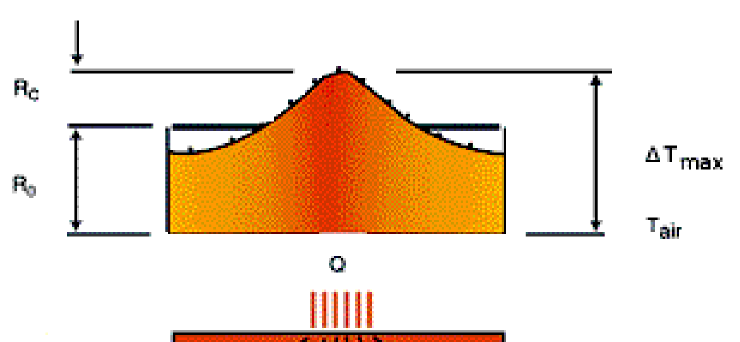
Material:
copper foil and a glass-reinforced polymer (FR-4).

$$k_i = f_i * k_{Cu},$$



Handbook of electronic packaging: Thermal design consideration, by J.Baum; other sources

Resistência térmica equivalente



- footprint or contact area of the heat source, A_s
- footprint area of the heat sink base-plate, A_p
- thickness of the heat sink base-plate, t
- thermal conductivity of the heat sink base-plate, k
- average heat sink thermal resistance, R_0

Rtotal = Ro + Rc

$$R_c = \frac{\sqrt{A_p} - \sqrt{A_s}}{k\sqrt{\pi A_p A_s}} \times \frac{\lambda k A_p R_0 + \tanh(\lambda t)}{1 + \lambda k A_p R_0 \tanh(\lambda t)} \qquad (1)$$

where

$$\lambda = \frac{\pi^{3/2}}{\sqrt{A_p}} + \frac{1}{\sqrt{A_s}} \qquad (2)$$

Erro: <5%

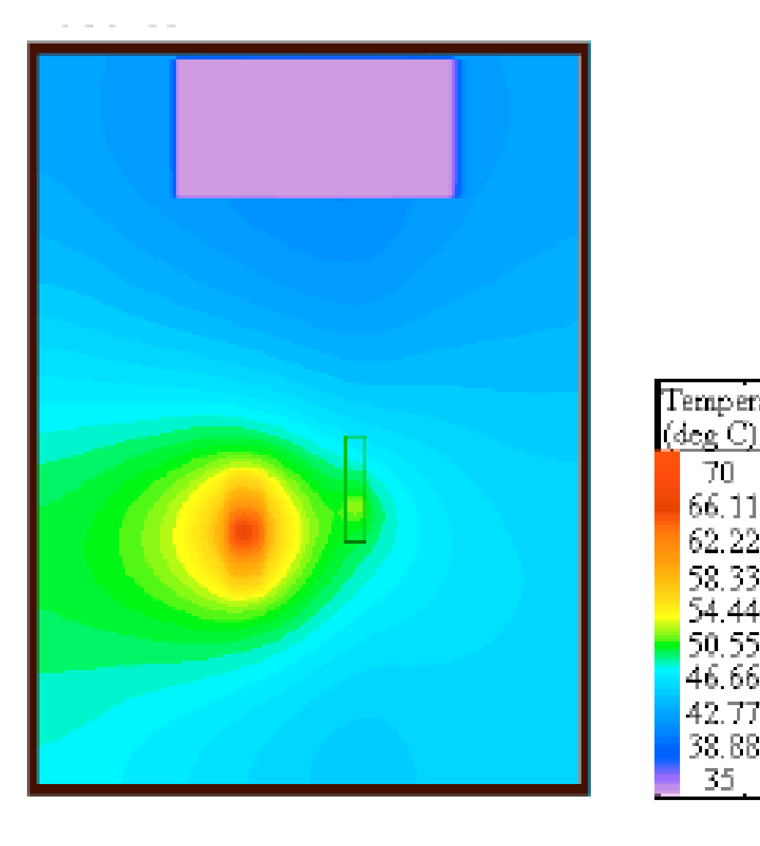
http://www.electronics-cooling.com/Resources/EC_Articles/JAN98/article3.htm

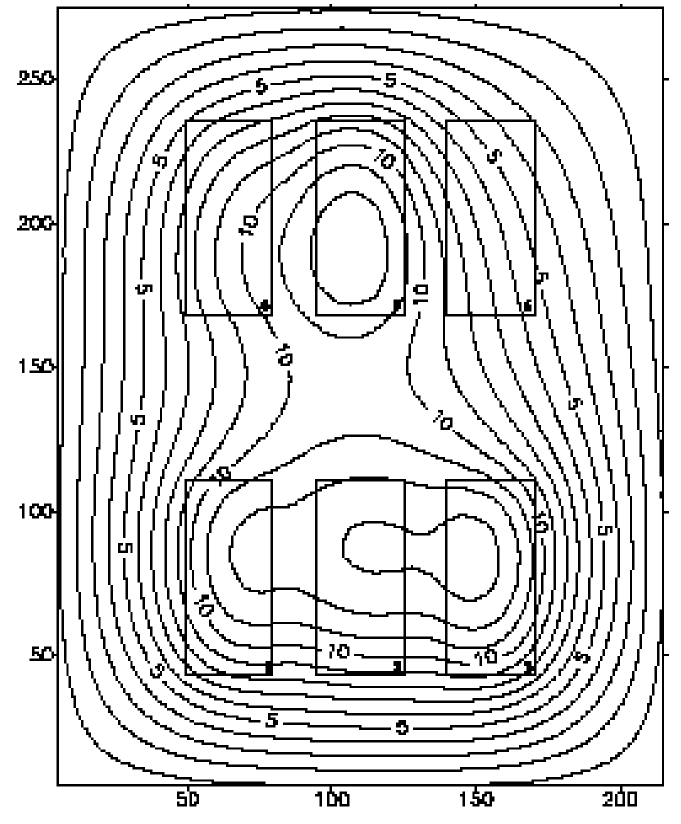
Influência de posição de aquecimento

$$Rtotal = Ro + C_f Rc$$

http://www.electronics-cooling.com/Resources/EC_Articles/JAN98/article3.htm

Campo de temperatura





http://www.thermacore.com/pdfs/cfd.pdf

ENCIT 2002

Software

FLOTHERM -The world's leading thermal analysis software for the electronics industry: Flomerics; Analysis Software

FLOPACK- Thermal Analysis of IC-Packages: Flomerics; Analysis Software

FLO/EDA - A Web-based tool for Creating Thermal Models of PCBs: Flomerics: Design Software

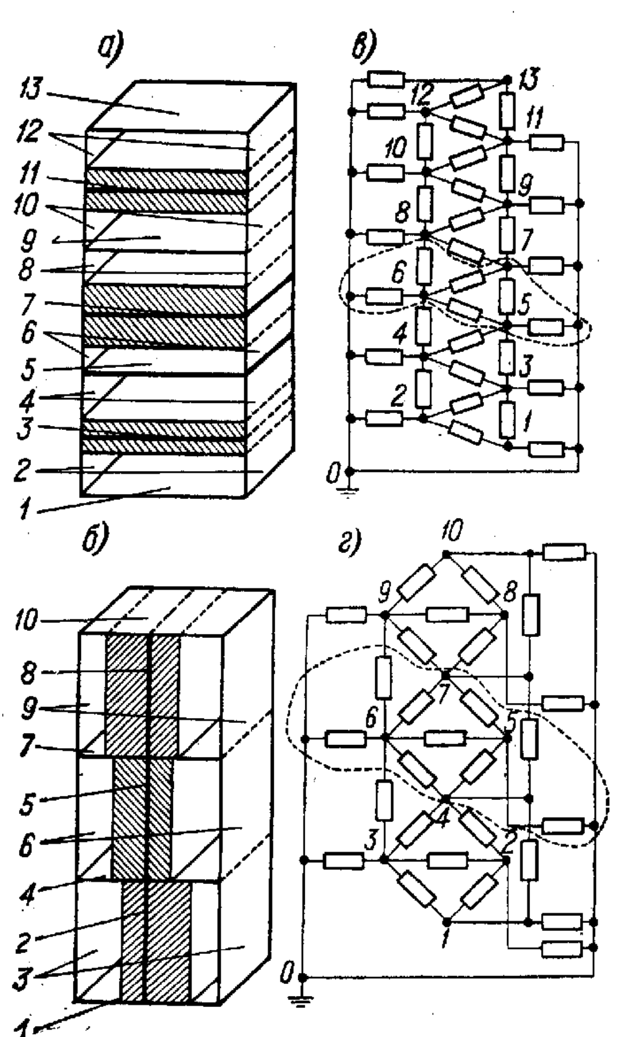
FLO/MCAD- Interfacing FLOTHERM with CAD Software: Flomerics: Design Software

http://www.coolingzone.com/cgi-bin/Members/search_products?frame=floor

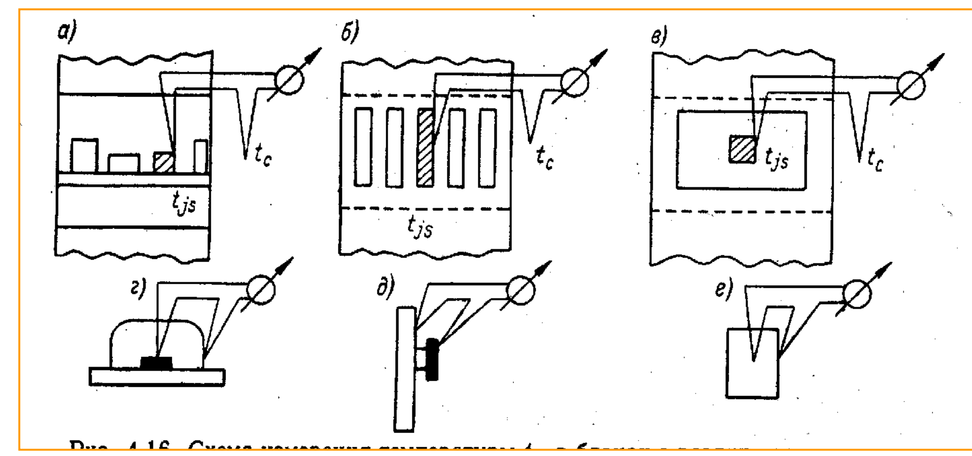
Caixa eletrônica

Handbook of electronic packaging: Thermal design consideration, by J.Baum; other sources

Modelagem pelo RC-analogia



Obtenção de resistências:



I.V.Glushitskiy, 1987; G.V.Reznikov, 1988

Condições de vácuo: influência na interface

TABLE 2. Thermal-contact-resistance Preliminary-design Guidelines

Description	Environmental pressure	Approximate interface pressure, psi	R_t, (°C)(in.²)/watt
Small stud-mounted components (such as stud-mounted transistors)	Sea level	5,000 500	0.05 0.50
	High vacuum	5,000 500	0.08 0.80
Mounting feet of equipment with contact areas of about 1 in.²	Sea level	1,000 100	0.5 1.0
	High vacuum	1,000 100	2.0 5.0
Large-surface contact areas	Sea level	100 10	1.0 3.0
	High vacuum	100 10	7.0 20.0

Handbook of electronic packaging: Thermal design consideration, by J.Baum;

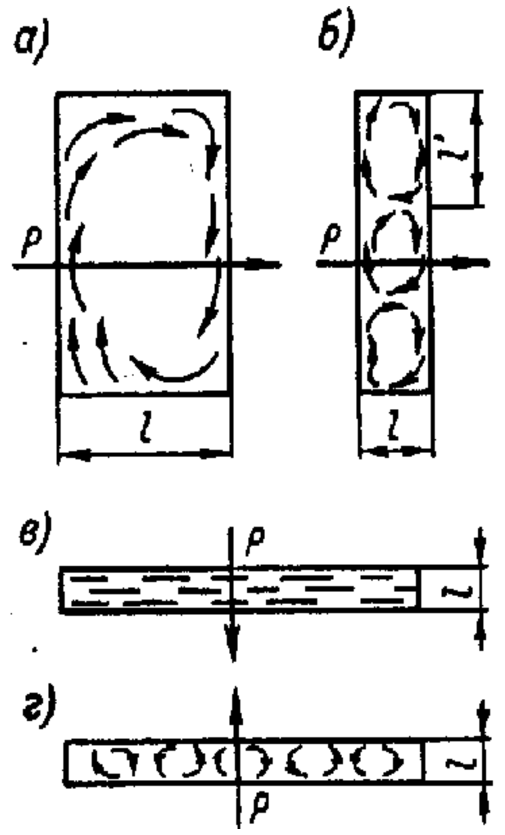
Condições de vácuo: Influência de montagem

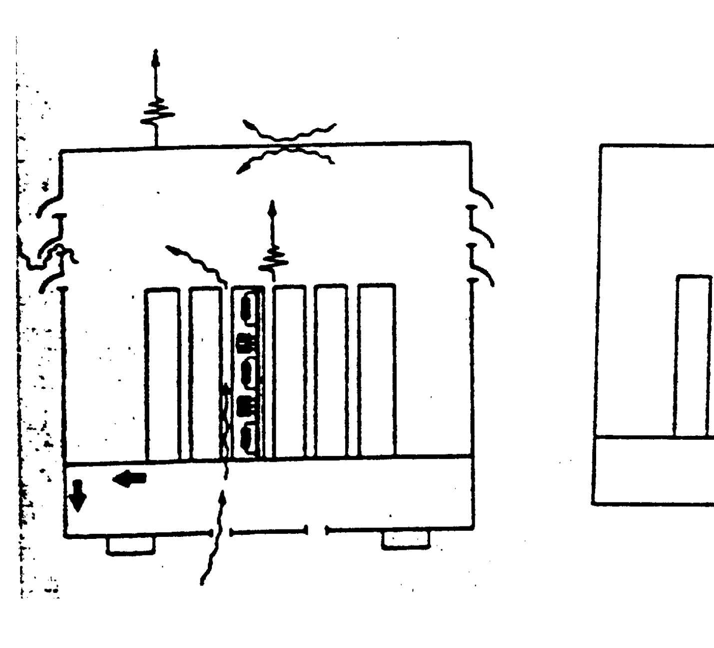
TABLE 10. Resistor Surface-to-mounting Thermal Resistance

Resistor-mounting configuration	Type watts	Thermal resistance, °C/watt	
		Sea level	Vacuum
(a) Conformal coating; Aluminum plate	¼	87	105
	½	67	90
	1	43	73
(b) Conformal coating; Terminal; Aluminum plate; 1/2	¼	79	97
	½	65	87
	1	40	58
(c) Terminal; 1/32 gap; Aluminum plate; 1/2	¼	146	214
	½	108	176
	1		
(d) Partial fillet of conformal coating; Terminal; 0.02 gap before coating; Aluminum plate; 1/2	¼	135	192
	½	86	142
	1	64	112
(e) Conformal coating; Terminal; Aluminum plate; 1/16	¼	78	95
	½	66	82
	1	39	57

Handbook of electronic packagir
Thermal design consideration,
by J.Baum;

Condições de vácuo vs convecção natural





Handbook of electronic packaging: Thermal design consideration, by J.Baum; other sources

Condições de vácuo vs convecção natural

MLI, vacuum

Vacuum, Tw=20 oC

Ambient, 20 oC

Temperature, oC

50
40
30
20
10

0 4000 8000 12000

time, sec

INPE: CIMEX

Soluções para densidades elevadas de fluxo de calor: um exemplo

http://www.cfdrc.com/applications/microelectronics/experiment.html

Participação de um engenheiro térmico no projeto de componentes eletrônicos

"...We believe that thermal designers are both critical and most useful in the early conceptual stages of product design.."

"..The point of these curves is that your intuition or some quick hand calculations early in the design process is sometimes worth more than all of the CFD analysis work at the end of the design process

1A. Band-Aid Approach

Risk

PANIC!

Critical path
Compromised design

Correlations
Modeling
Testing

Product Development Time

Start Production

1B. Concurrent Approach

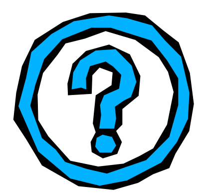
Risk

Intuition
Correlations
Modeling
Validation

Meets schedule
Optimized design

Product Development Time

"Electronic-cooling" Effective Thermal Design for Electronic Systems, by C. L. Belady



Sunpower Inc, Stirling linear, counterbalanced, 77K, 100W/4W