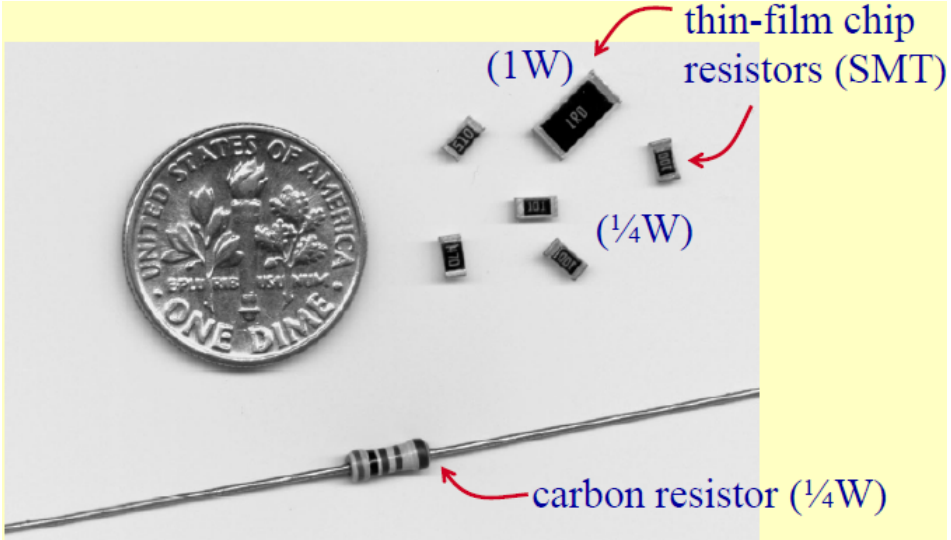
Lecture 7 Passive RLC Components (1)

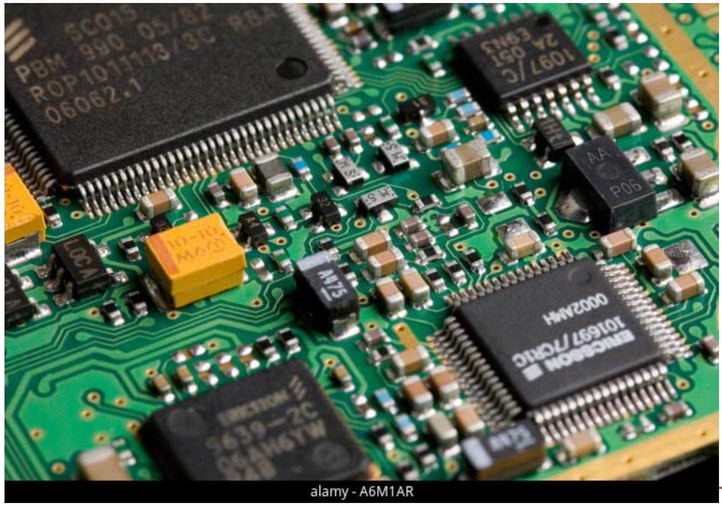
1. Resistors for High Frequencies
2. Resistor Specifications
3. Bulk Metal Foil Resistors
4. Wirewound Resistors
5. Thick-film Resistors
6. Thin-film Resistors
7. Resistor Frequency Characteristics
8. SMT Resistor Equivalent Circuit Modeling
9. Coding Examples

1. Resistors for High Frequencies

- Resistors for RF & MW applications: *SMT*, *small*



- SMT (surface mount) resistors

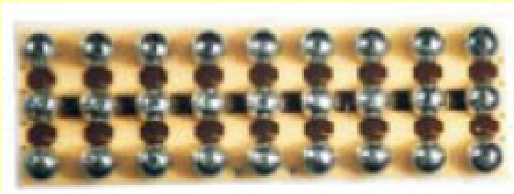


SMT resistor packaging forms

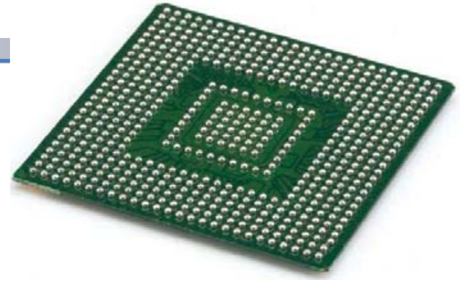
0603 chip

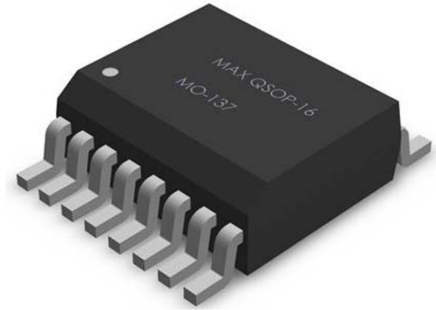
QSOP

BGA



Best to worst:
1) BGA
2) 0603 chip
3) QSOP
4) Axial leaded





- *0603 chip*: 0.06"×0.03"=1.6×0.8mm
- *QSOP* (quarter-size small outline package)
- *BGA* (ball grid array)

▪ SMT chip components size

- EIA (Electronic Industry Association): 미국전자산업협회

- SMT chip component size: *EIA inch* (imperial) = standard

Rectangular Chip Component Package Sizes

Table of Chip Package Size Codes and Dimensions			
EIA (inch) Name	Inch Dimensions	IEC (metric) Name	Metric Dimensions
01005	0.0157 in × 0.0079 in	0402	0.4 mm × 0.2 mm
0201	0.024 in × 0.012 in	0603	0.6 mm × 0.3 mm
0402	0.039 in × 0.020 in	1005	1.0 mm × 0.5 mm
0603	0.063 in × 0.031 in	1608	1.6 mm × 0.8 mm
0805	0.079 in × 0.049 in	2012	2.0 mm × 1.25 mm
1008	0.098 in × 0.079 in	2520	2.5 mm × 2.0 mm
1206	0.126 in × 0.063 in	3216	3.2 mm × 1.6 mm
1210	0.126 in × 0.098 in	3225	3.2 mm × 2.5 mm
1806	0.177 in × 0.063 in	4516	4.5 mm × 1.6 mm
1812	0.18 in × 0.13 in	4532	4.5 mm × 3.2 mm
2010	0.197 in × 0.098 in	5025	5.0 mm × 2.5 mm
2512	0.25 in × 0.13 in	6332	6.4 mm × 3.2 mm
2920	0.29 in × 0.20 in	7451	7.4 mm × 5.1 mm

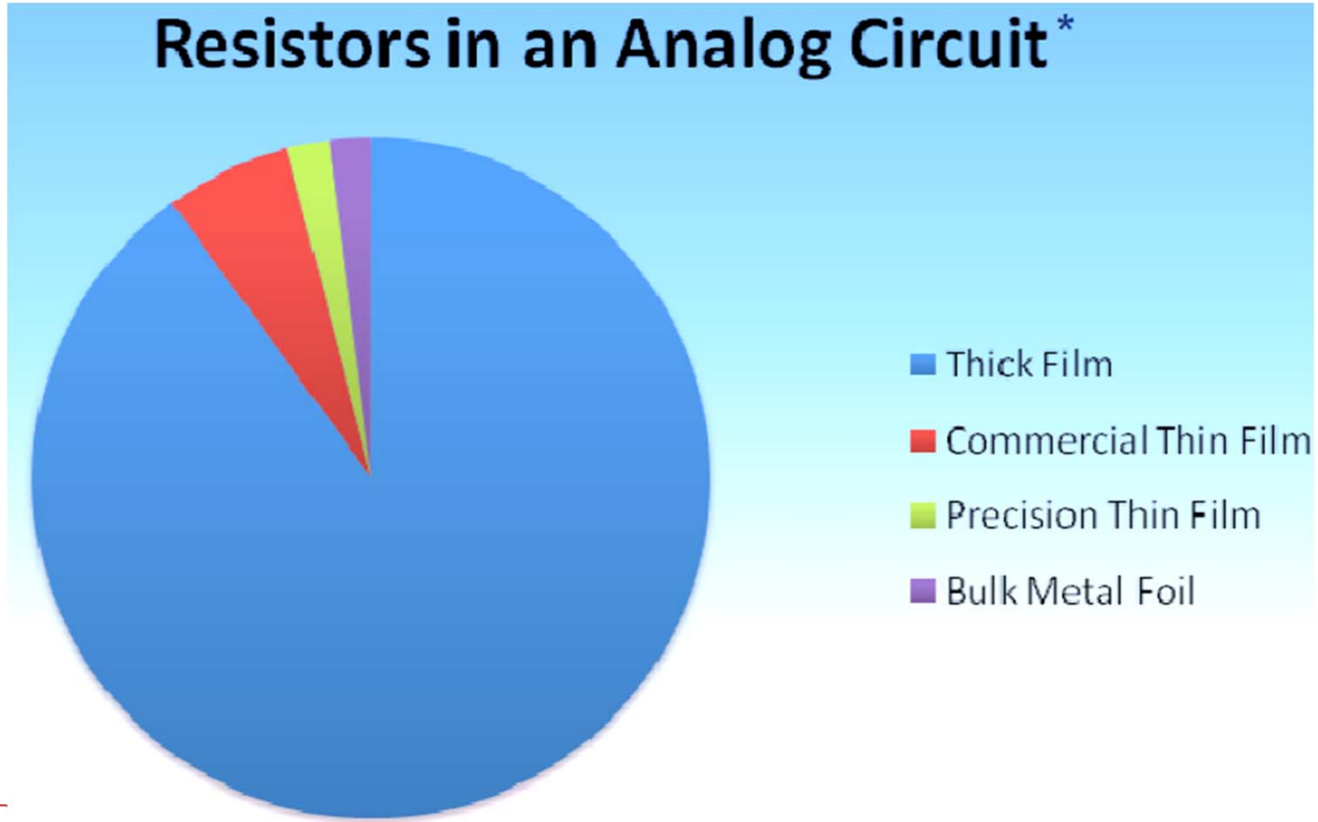
- Resistive element forms

- *Wirewound*

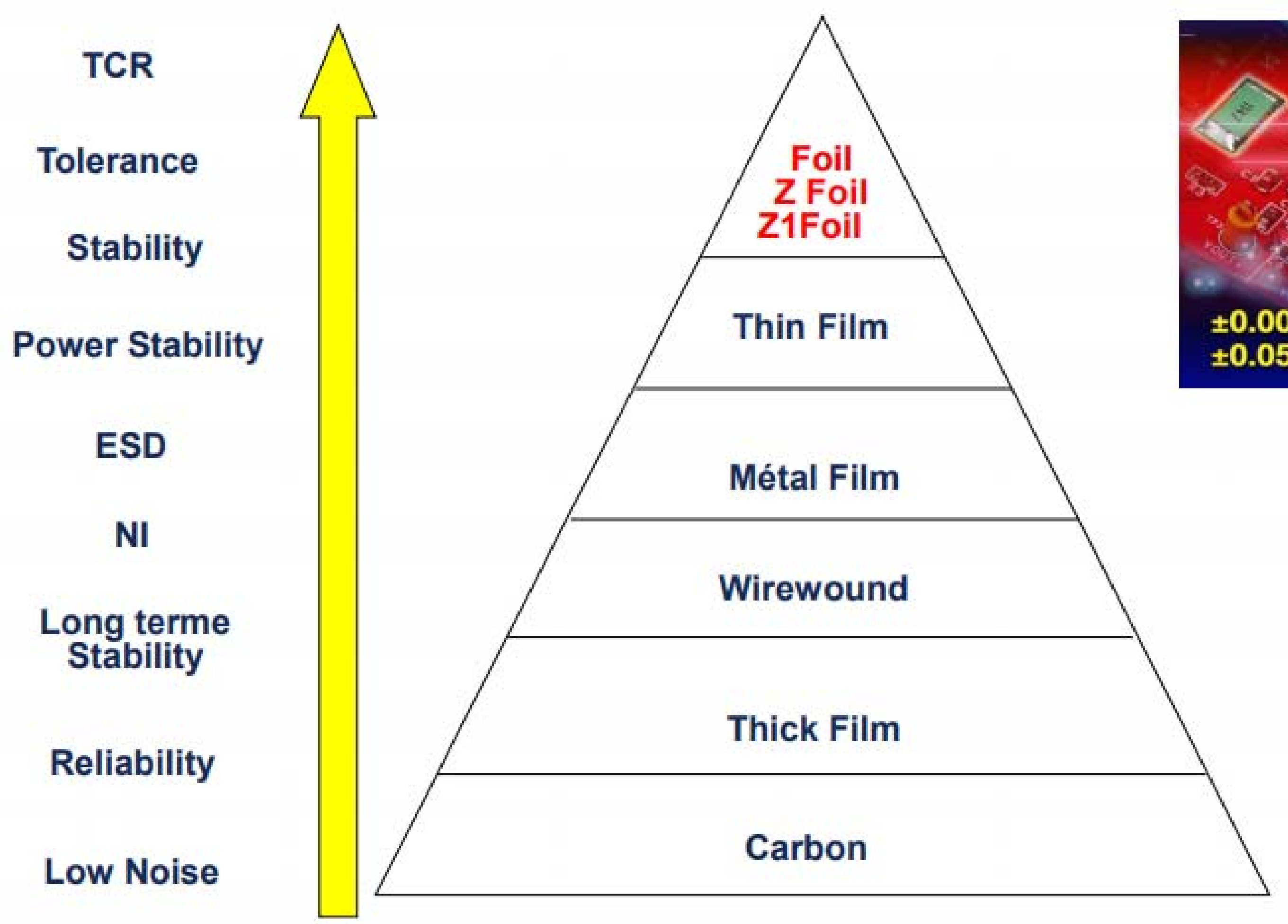
- *Thin film*

- *Thick film*

- Bulk *metal* conventional *foil* and Z-foil



Resistor evolutions

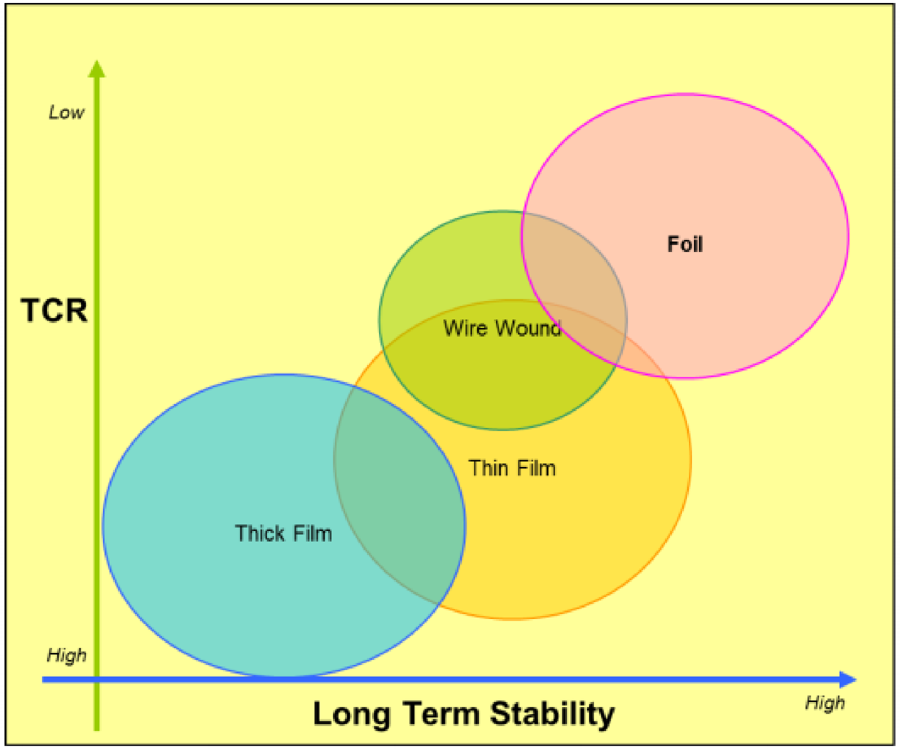


MOQ: 1
RV: 1K1234
Tol.: 0.001%
TCR: 0.2ppm/℃
ESD: >25KV
High Temp.: 240℃
Samples in 5 days

- TCR (temperature coefficient of resistance)
- ESD (electrostatic discharge), NI (noise immunity)
- MOQ (minimum order quantity), RV (resistance value)

Performance comparison of different resistor types

Technology	Temperature Coefficient of Resistance (TCR) -55°C to +125°C, +25°C ref.	Initial Tolerance	End of Life Tolerance	Load Life Stability at +70°C, Rated Power 2000 Hours and 10,000 Hours	ESD (V)	Thermal Stabilization	Noise (dB)
Bulk Metal® Foil	±0.2 ppm/°C	From 0.001%	<0.05%	0.005% (50 ppm) 0.01% (100 ppm)	25,000	<1 second	-42
High-Precision Thin Film	±5 ppm/°C	From 0.05%	<0.4%	0.05% (500 ppm) 0.15% (1500 ppm)	2500	>few minutes	-20
Precision Thick Film	±50 ppm/°C	From 0.5%	<5%	0.5% (5000 ppm) 2% (20,000 ppm)	2000	>few minutes	+20
Wirewound	±3 ppm/°C	From 0.005%	<0.5%	0.05% (500 ppm) 0.15% (1500 ppm)	25,000	>few minutes	-35

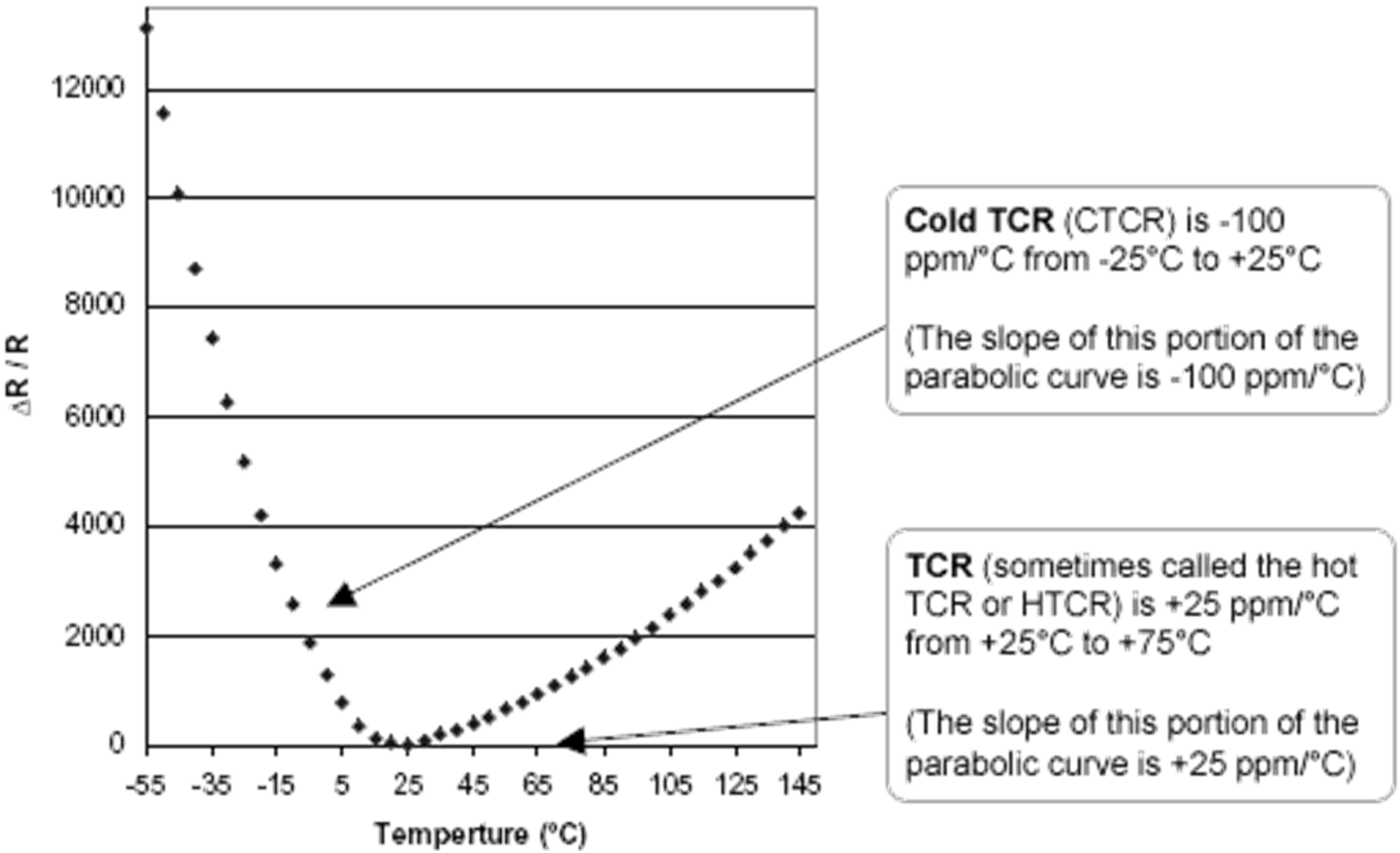


2. Resistor Specifications

- Resistor specifications (ex: Vishay high-precision bulk metal foil type)

- Resistance value (RV): 1K1234
- TCR (temperature coefficient of resistance): ±2ppm/°C
- Tolerance: ±0.01%
- ESD (electrostatic discharge) sensitivity: 25kV
- Maximum working voltage
- Power rating: 0.5W @ +70°C
- Rated voltage
- Load life stability
- Current noise
- Thermal stabilization: speed of reaction to current flow and ambient temperature change, < 1 s
- Nonlinearity: change of R with V: < 0.1ppm/V
- Response time and speed: due to parasitic L and C, rise time 1ns

- TCR curve



12000
10000
8000
6000
4000
2000
0
ΔR / R
-55 -35 -15 5 25 45 65 85 105 125 145
Temperture (°C)
Cold TCR (CTCR) is -100 ppm/°C from -25°C to +25°C
(The slope of this portion of the parabolic curve is -100 ppm/°C)
TCR (sometimes called the hot TCR or HTCR) is +25 ppm/°C from +25°C to +75°C
(The slope of this portion of the parabolic curve is +25 ppm/°C)

- Temperature-related effects

- TCR (temperature coefficient of resistance): TCR = ΔR / ($R_{\mathrm{ref}}\,\Delta T$)

- PCR (power coefficient of resistance): resistance due to self-heating

- Thermal EMF: caused by temperature between the two junctions of dissimilar materials. A significant noise source in high-precision resistor for low resistance DC applications

- ESD (electrostatic discharge): high voltage discharge through a resistor causing a catastrophic failure or latent defect

- STO (short time overload): a temporary unexpected high pulse or overload causing parametric or catastrophic failure. STO is an accelerated simulation of load life stability

- Thermal stabilization: how quickly a resistor stabilizes at its final value after being subjected to its full rated power

- Stability

- Exposure to electrical stresses: current flow → heat generated → mechanical stresses

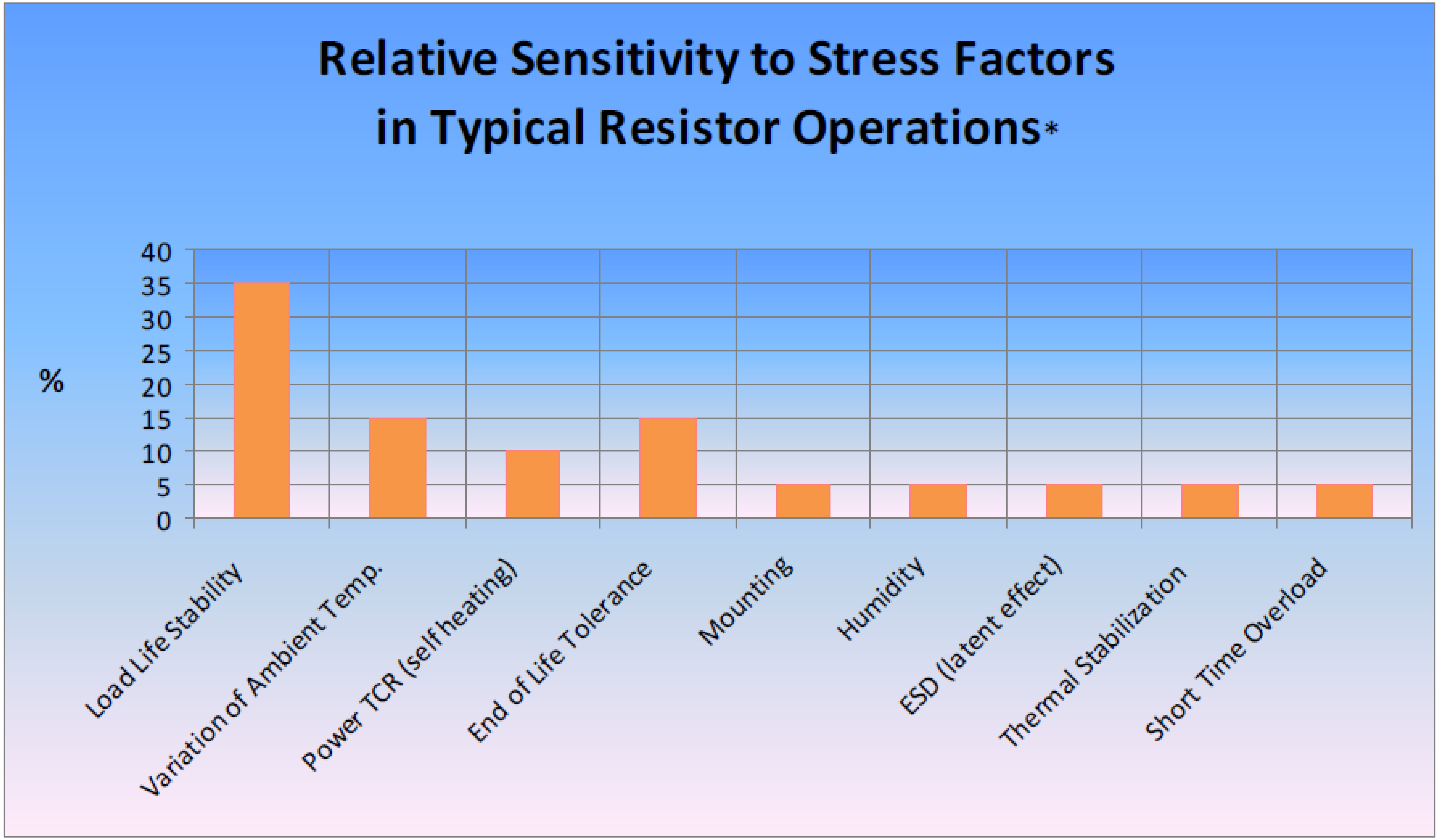
- Ambient temperature variations → mechanical stresses

- Chemical stresses

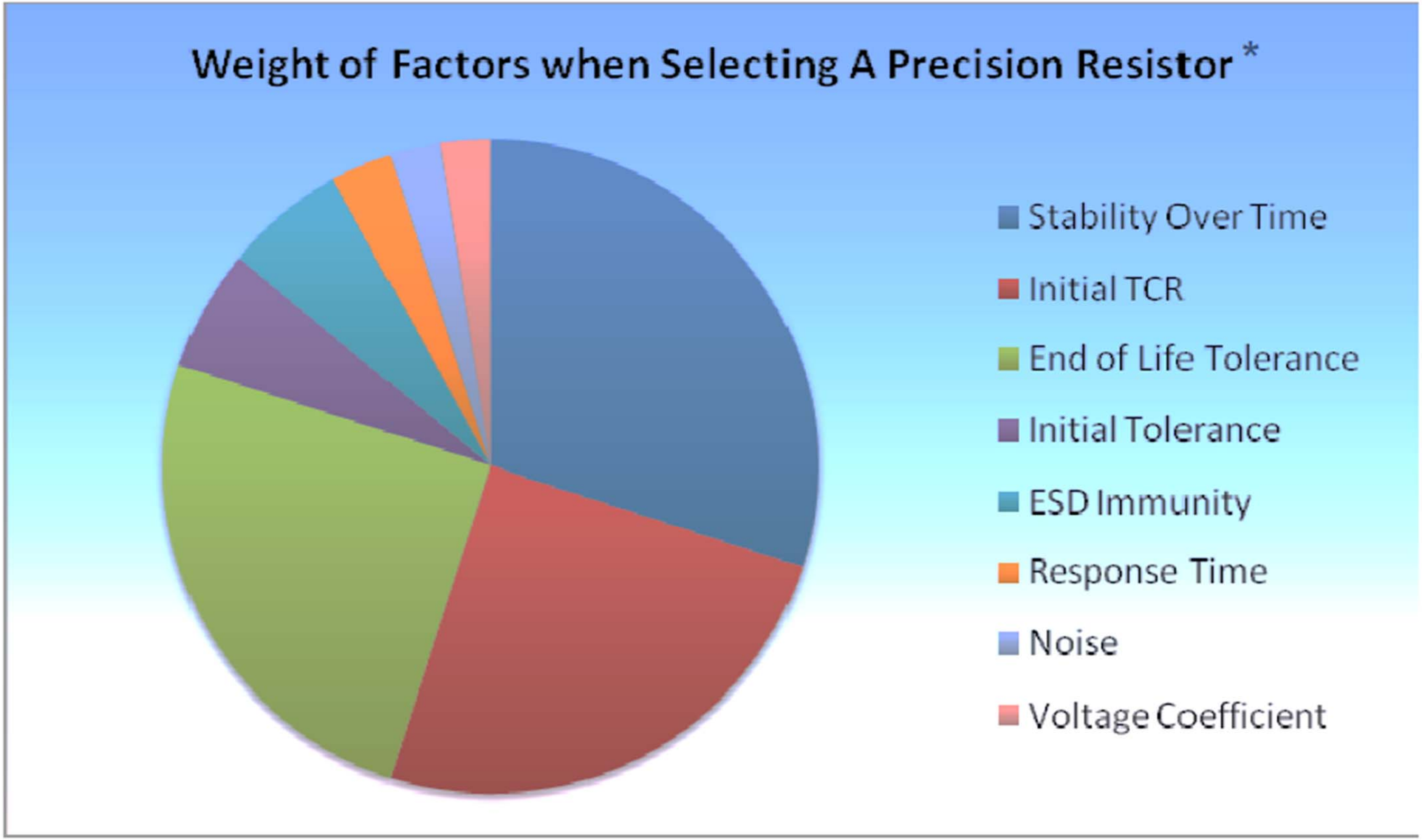
- For good stability

- Materials and design for precise thermo-mechanical balance

- Resistor sensitivity to stress factors



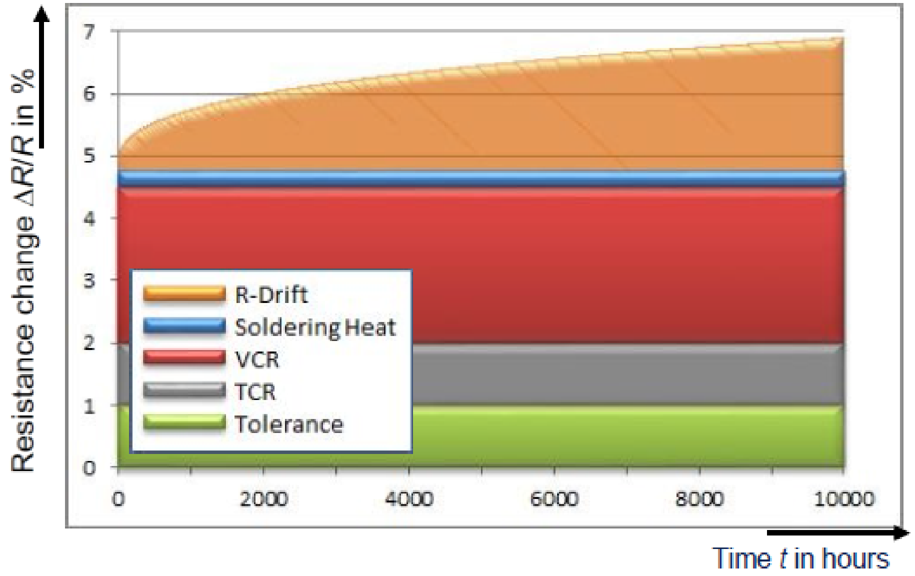
What Factors Do Design Engineers Look For?



- Stability of thick-film and thin-film reistors

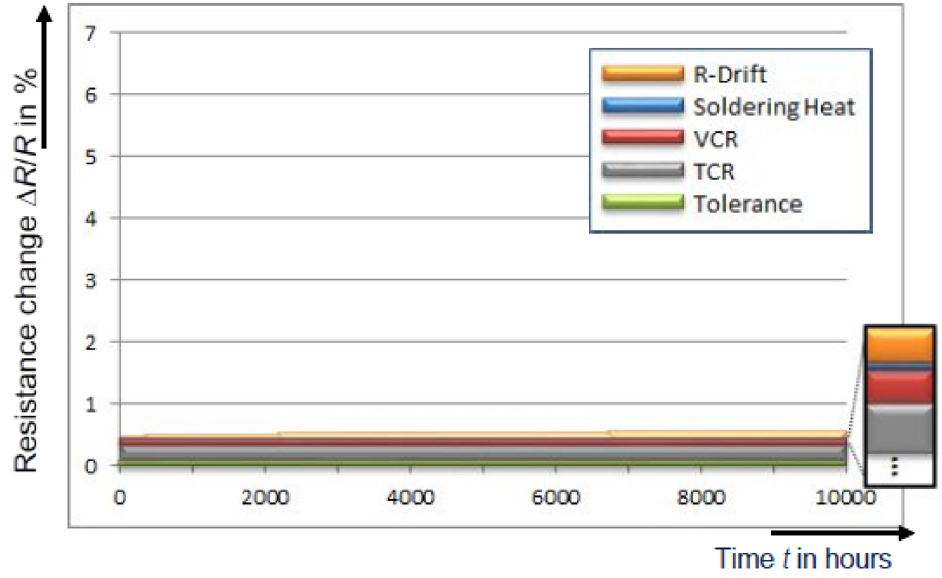
Typical High Voltage Thick Film Chip Resistor

- TCR ± 100 ppm/^{0}C, tolerance ± 1%, VCR < 25 ppm/V



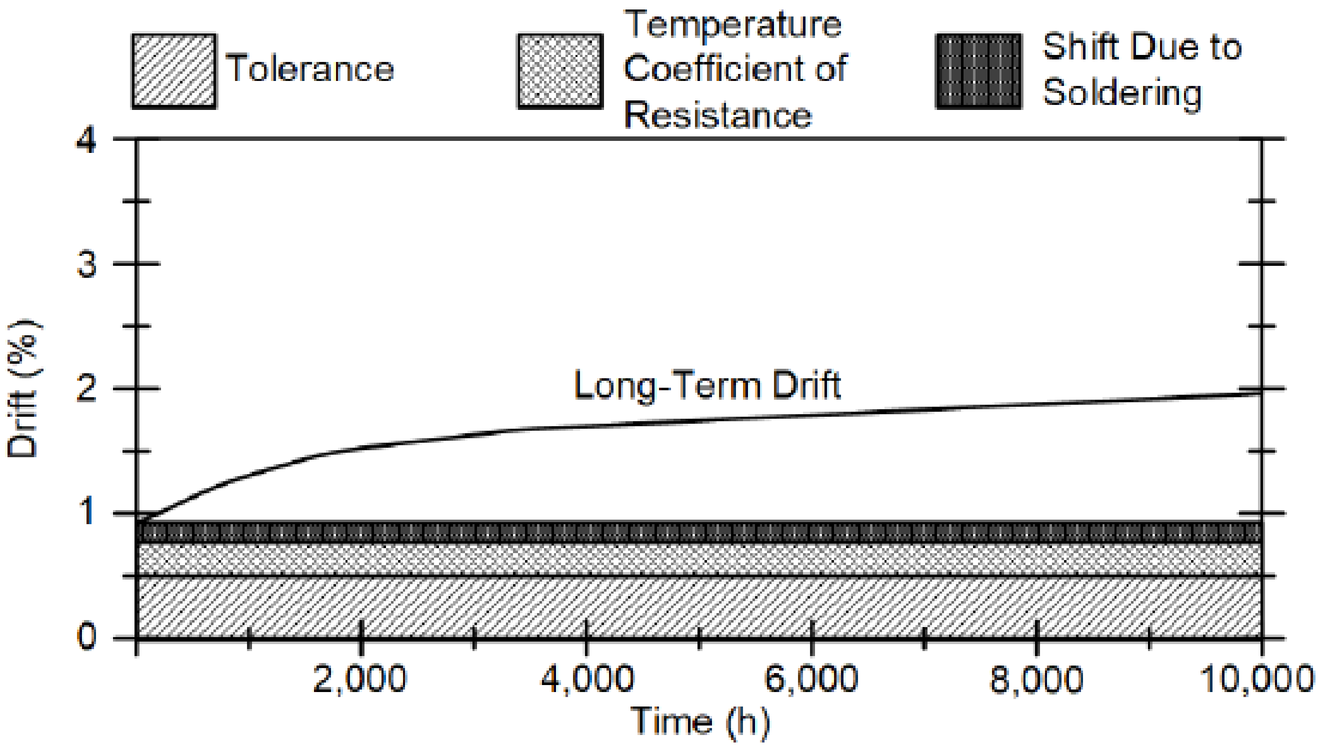
TNPV High Voltage Thin Film Chip Resistor

- TCR ± 25 ppm/^{0}C, tolerance ± 0.1%, VCR < 1 ppm/V



Source: Vishay

- Worst-case tolerance stack-up for thin-film resistors



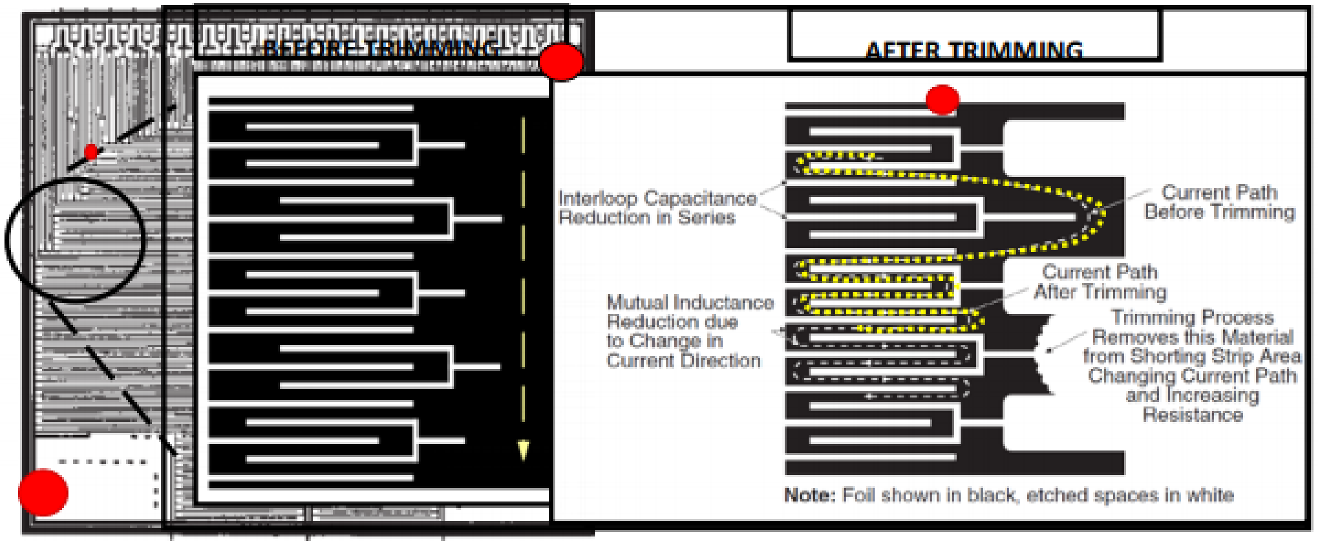
Source: T. C. Mallett, IEEE T-IM, 68(11), 2019

3. Bulk Metal Foil Resistors

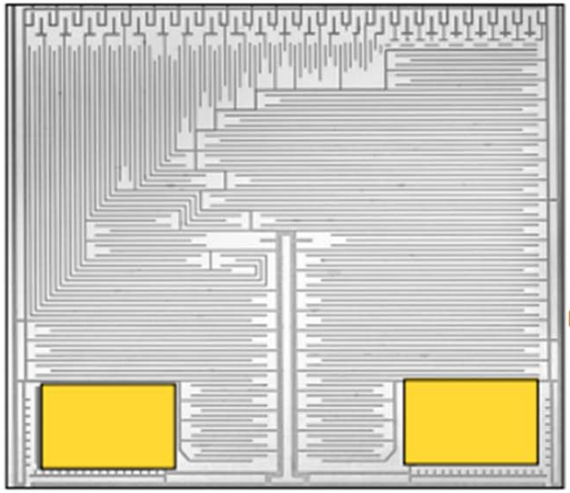
Introduction

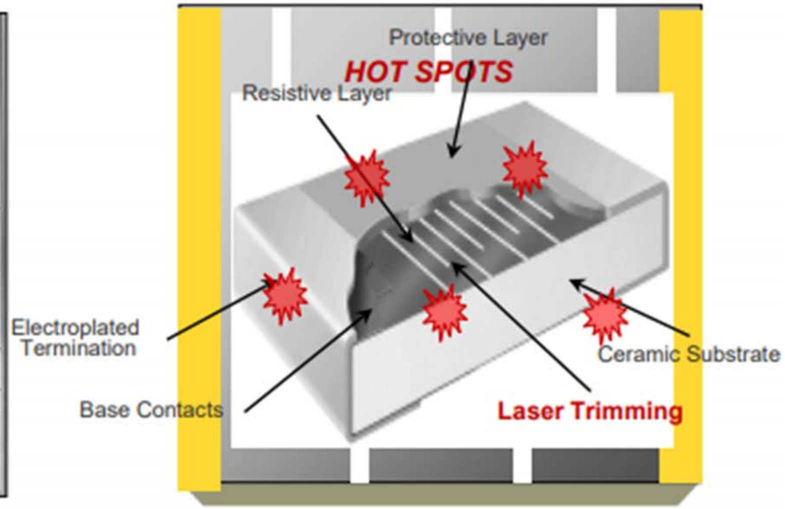
The Bulk Metal® Foil is photo etched into a resistive pattern (no mechanical stress introduced). Later, it is adjusted (manually or by laser) to any desired value and tolerance.

Because the resistive metal used is not drawn, wound, or mechanically stressed in any way during manufacturing process, the Bulk Metal ® Foil resistor design maintains all of its inherent physical and electrical characteristics - while winding of wire, or sputtering of thin films, or thick film glazing do not.

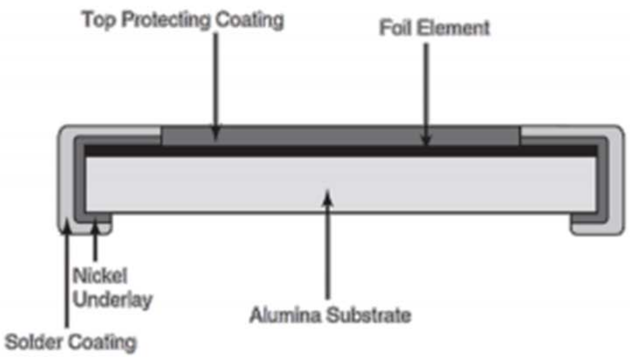


- ## Structure

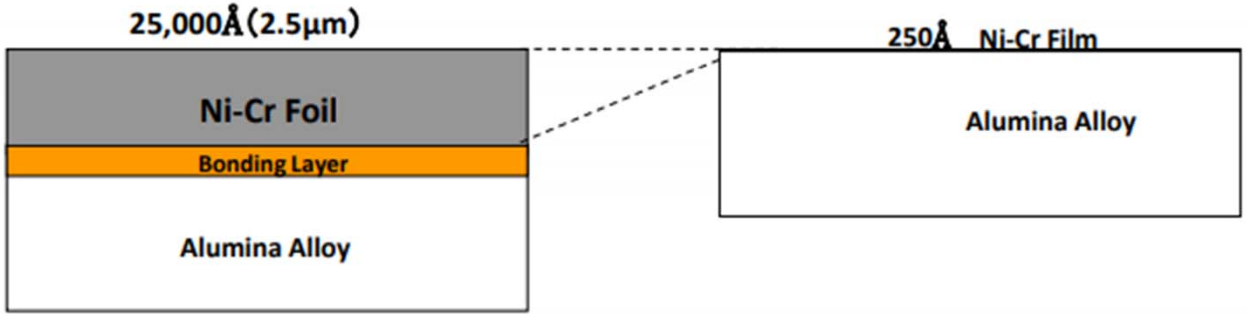




Protective Layer
HOT SPOTS
Resistive Layer
Electroplated Termination
Ceramic Substrate
Base Contacts
Laser Trimming



Top Protecting Coating
Foil Element
Nickel Underlay
Alumina Substrate
Solder Coating



25,000Å (2.5μm)
Ni-Cr Foil
Bonding Layer
Alumina Alloy
250Å Ni-Cr Film
Alumina Alloy

- Advantages

Stability

- Time=The Lowest Long Term Stability (2 ppm/year for 6 years)
- Temperature=The Lowest TCR (0+/-0.05 ppm/°C possible)

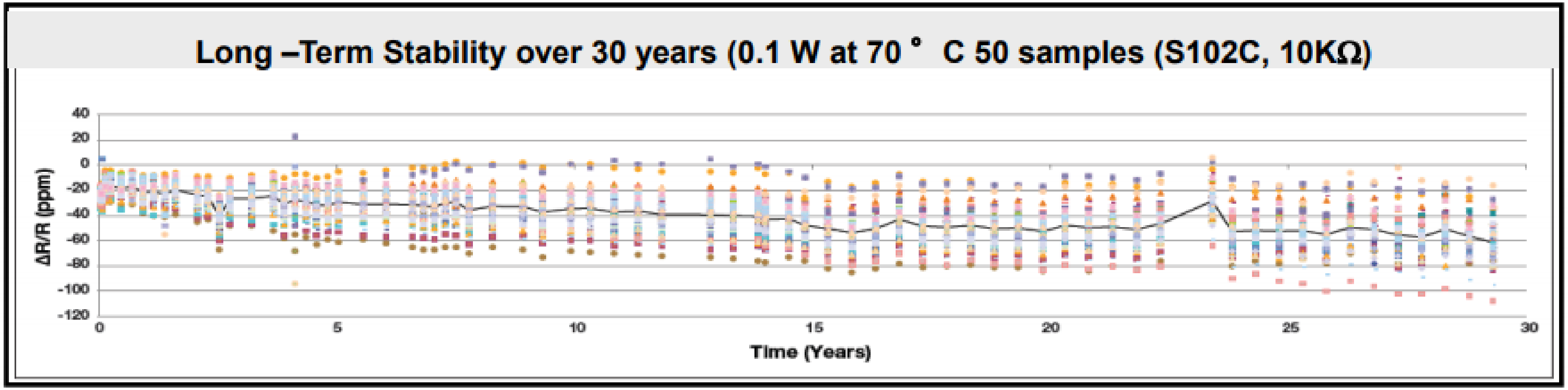
Reliability

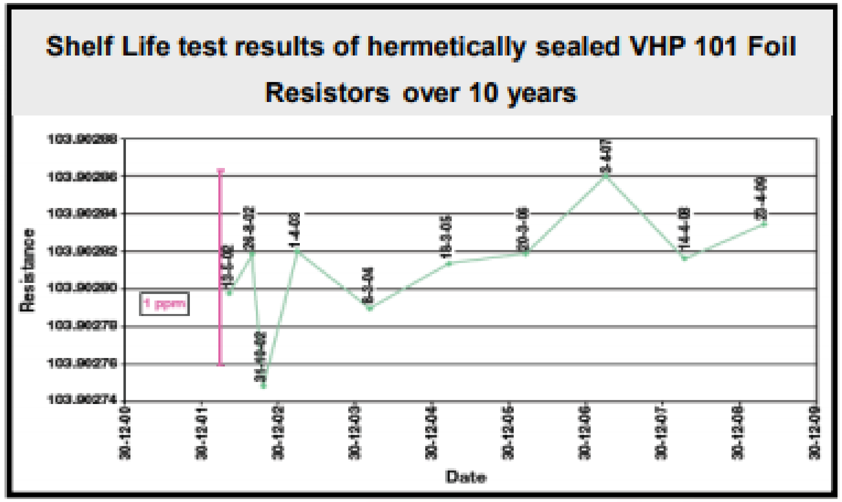
- Reliability Tests= According to MIL-PRF-55182/9 & MIL-PRF-55342

Accuracy

- The Tightest Tolerance (to ±0.001%)

- Long-term stability of bulk metal foil resistors





Key Characteristics of Bulk Metal® Foil Resistors

Temperature Characteristics of Resistance:

0.14 ppm/°C (typical)

Resistance Tolerance:

±0.005%

Long Term Stability:

5 ppm/year, 10 ppm/3 years (hermetically-sealed)

Load Life Stability:

0.005%/2000 hours

Thermal EMF:

0.1 µV/°C (between leads)

Noise:

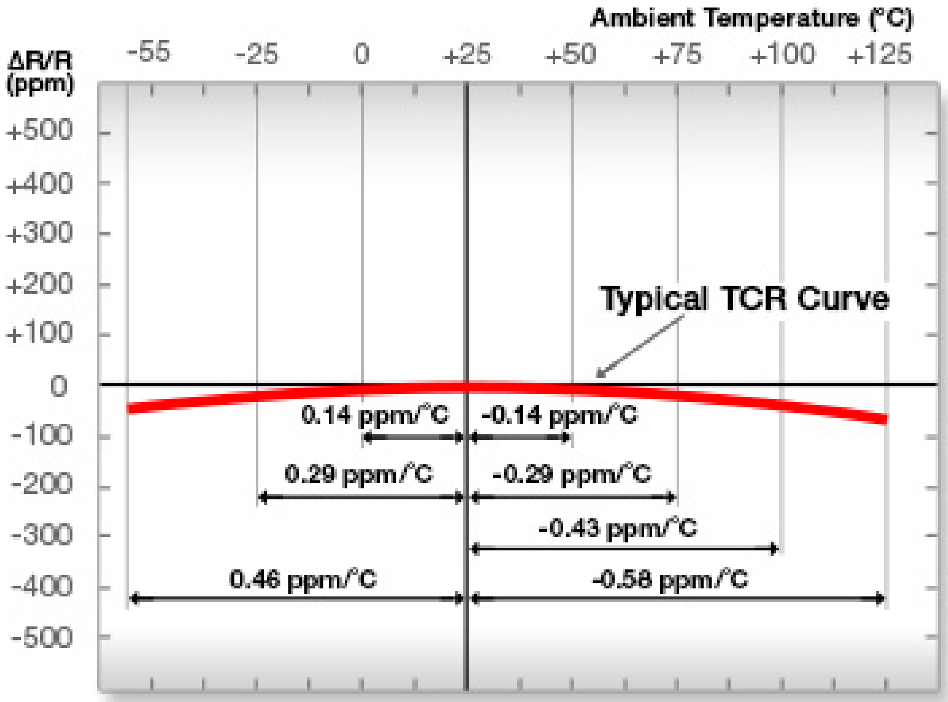
-42 dB

Voltage Coefficient:

0.1 ppm/V

Frequency Characteristics:

Inductance: 0.08 µH/capacitance: 0.5 picofarad

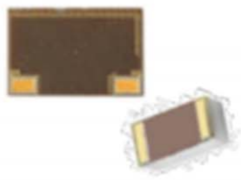
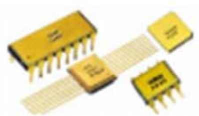


- Various forms of bulk metal foil resistors

- Applications of bulk metal foil resistors

  - Measurement systems
  - Current sensing
  - High–precision amplifiers
  - Weighing systems
  - Force balance scales
  - Differential amplifiers
  - Switching power supplies
  - Electron microscopes
  - Gyro navigation controls
  - Pressure sensors
  - Motor speed controls
  - Telecommunications
  - Bridge networks
  - Standard Box & Decade
  - Tailored solutions per customer specifications

- High-temperature bulk metal foil resistors

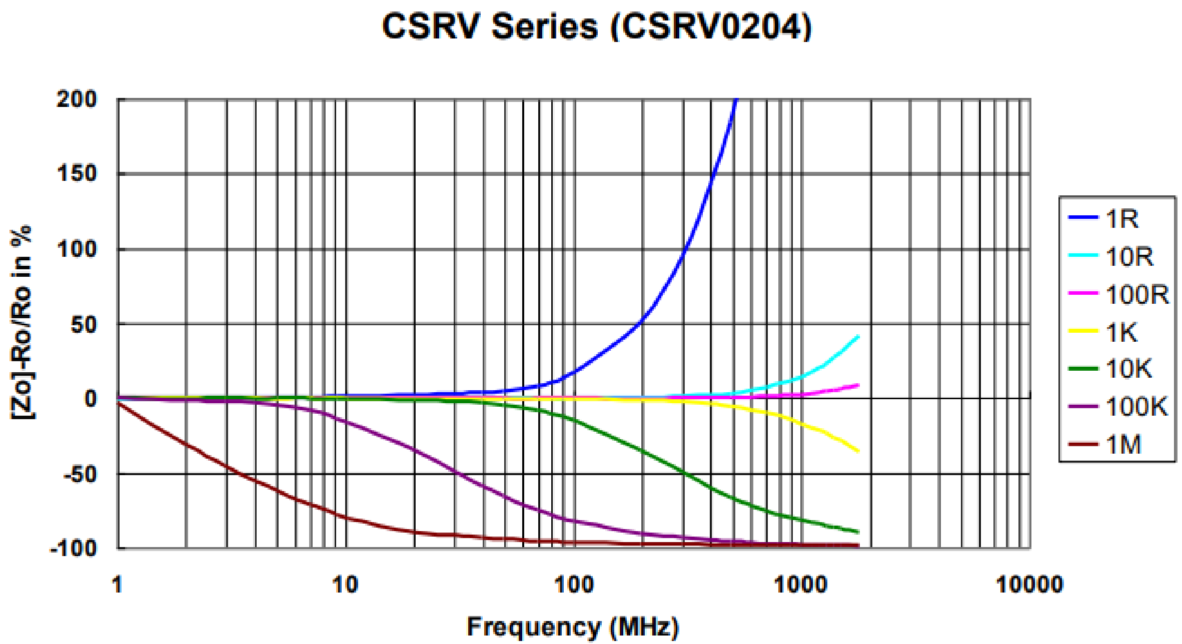
Product Name	Product Image	Type	Features	Max working Temperature
HTHG		High Temperature Chip Resistor Sizes: 5x5,15x5,15x10 0603,0805,1206, 1506,2010,2512 Mounting: Face up only	Z1- Foil technology Mounting/Connection Method: Face up: Gold wire bonding	+240˚C
HTHA		High Temperature Chip Resistor Sizes: 0603,0805,1206, 1506,2010,2512 Mounting: Face up & face down	Z1- Foil technology Two Options of Mounting/Connection Methods: 1. Face up: Aluminum wire bonding 2. Face down: Conductive epoxy	+240˚C
PRND		Hermetically Sealed Network	Includes **HTHG** chips inside	+230˚C
FRSH		Sizes: 0603,0805,1206 1506,2010,2512 High Temperature/ Power Surface Mount Chip Resistor (Wrap around)	Z1- Foil technology **Extended Pads**	+225˚C

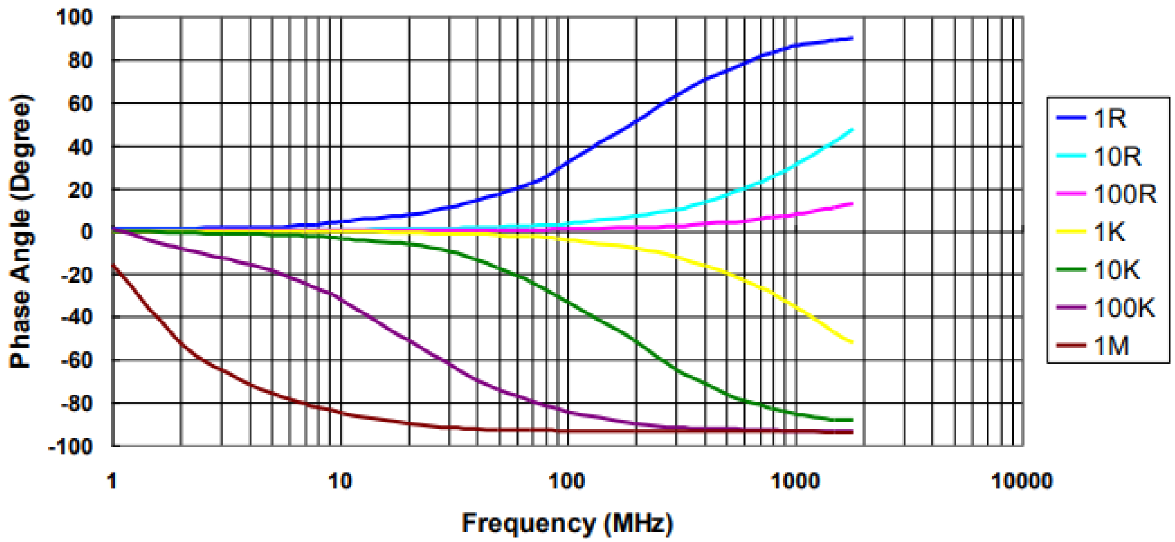
▪ Precision metal film resistors

- Produced by Viking Co.

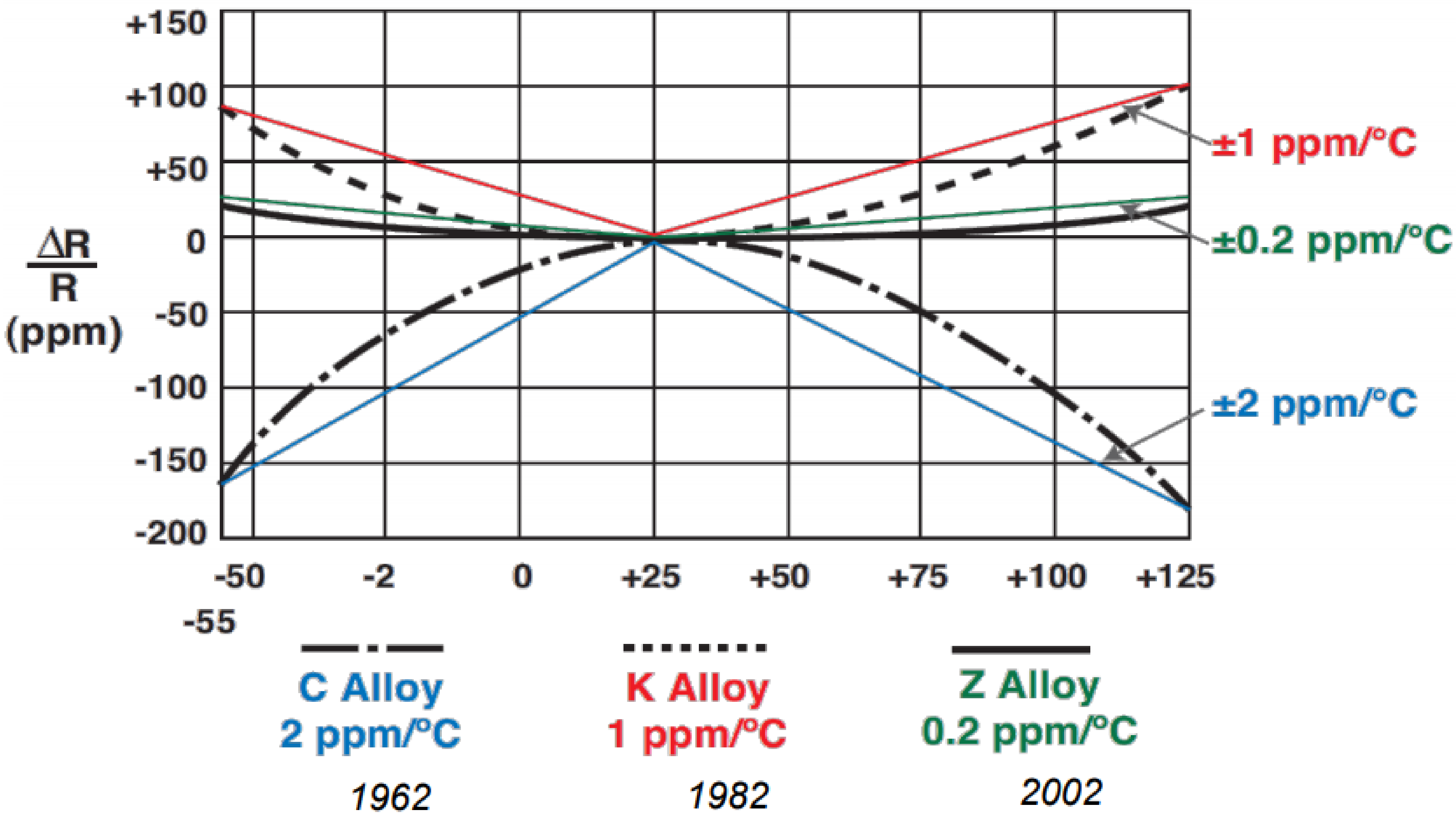
TECHNICAL SPECIFICATIONS							
DESCRIPTION	CSRV0102			CSRV0204		CSRV0207	
Resistance range	1Ω-1MΩ; 0Ω			0.1Ω-3.4MΩ; 0Ω		0.1Ω-3.4MΩ; 0Ω	
Resistance tolerance	±5%;±1%;±0.5%;±0.25%;±0.1%						
Temperature coefficient	±100ppm/℃; ±50ppm/℃; ±25ppm/℃; ±15ppm/℃			±100ppm/℃; ±50ppm/℃; ±25ppm/℃; ±15ppm/℃; ±10ppm/℃; ±5ppm/℃			
Operation mode	Standard	High power		Standard	High power	Standard	High power
Power rating P_{70}	1/8W	1/5W	0.3W	1/4W	2/5W	1/2W	1W
Operating voltage $U_{max.}$	150V	200V	200V	200V	200V	300V	350V
Operating temperature range	-55℃~155℃						
Max. resistance change at P70 for resistance range, ΔR/R max., after 1000 h	≦0.5%			≦0.5%		≦0.5%	

- Precision metal film resistors, frequency response





- Very low TCR of bulk metal foil resistors



Metal foil resistor products example

- Prominent companies producing bulk-metal foil resistors

- Texas Components, www.texascomponents.com

- Vishay Precision Group: provides a good library of technical documents

  https://vpgfoilresistors.com/

  http://www.vishaypg.com/foil-resistors/

- Viking (a Taiwan company)

4. Wirewound Resistors

- Wirewound resistors

- Superior *surge* handling

- *Linear PTC* resistors

- For *low frequency*: due to parasitic inductance and capacitance

- *Encapsulation*: vitreous enamel, cement, silicon lacquer/plastic molding, finned aluminum housing

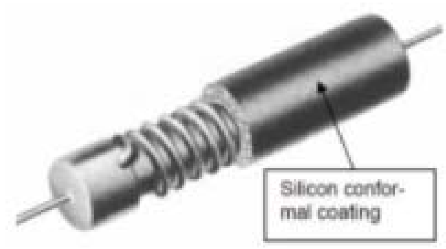
- Types

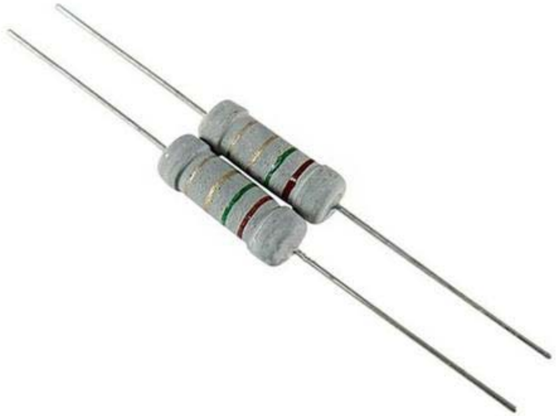
  Precision wirewound resistors

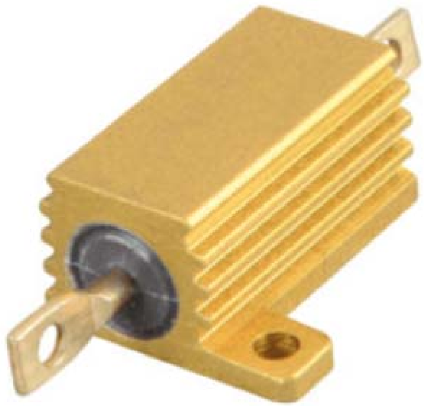
  Wirewound resistors for *power*-dissipating roles

  Low-ohm wirewound resistors: 5 - 800 mΩ

- Wirewound resistor forms







- Applications of precision wirewound resistors

- *Battery-testing equipment*
- *X-ray equipment Flowmeters*
- *Power supplies Medical Equipment*
- *Transducers Instrumentation*
- *Lighting controls*
- *Telecommunications*
- *Machine tools*
- *Motor controls*
- *Metering systems*
- *Industrial power drives*
- *Computers and peripherals*
- *Industrial control systems*
- *Gas monitoring systems*
- *Engine monitoring systems*
- *Telephone switching systems*

- Inductance and capacitance of wirewound resistors

Style acc to MIL-R-39007	Measures mm Φ^2	L	Power, W P @ 25°C	Inductance µH	Capaci-tance, pF
RWR 81	2.2	6.4	1	0.08···0.1	0.2
RWR 80	2.4	10.3	2	0.06···0.2	0.8
RWR 89	4.8	14	3	0.1···0.4	0.8
RWR 74/84	7.9	22	5	0.3···0.6	1 / 0.8
RWR 78	9.5	45	10	0.5···1.1	0.8

Characteristics of general wirewound resistors

CHARACTERISTIC / DESCRIPTION	DATA / COMMENTS				
	DESIGN / PACKAGING				
	Plastic	Cement	Enamel	Aluminum housed	Low ohmic values
Resistance (Ω)	0.1···1M	0.1···30k	0.1···350k	5m···250k	5m···800m
Power (W)	0.5···200	2···20	3···500	5···250	2···20
Tolerance (±%)	0.05···5	5···10	1···10	0.05···10	0.5···20
Temperature range (°C)	-65/+275	-40/+250	-55/+350	-55/+275	-55/+275
Limiting (maximum) voltage (V)	40 / 4000	250/ 2500	120/ 4000	110/ 2000	
TC (ppm/°C)	±10···±90	-80···+140	±75···±100	±20···±150	±20···±600
Stability (Δ R/R, ±%)	0.5···3	< 5	< 5	0.5···3	<0.25
Noise (µV/V)	Negligible: < 0.1 (≥ |-140|dB)				
Voltage dependence (x10^{-}/V)	Negligible: < 1				
Inductance (µH)	0.02···2. Frequency range ≤ 50 kHz.				Negligible
Capacitance (pF)	0.1···2				Negligible
Most common **failure mode.**	**Open circuit.** Increasing failure rate when wire diameter Φ <0.1mm. Moisture + DC operation results in great corrosion risk (that is amplified by impurities in protecting lacquer/enamel). Connections between resistor wire and terminals are especially exposed.				—
Comparison with *Non-wirewound*	Stability, Pulse hardiness: —Better Price, reactance, size, reliability: — Poorer				—
Solderability	Fair	Fair	Poor	Fair	Fair
Avoid	Adjustable and beryllium oxide cores.				—
Recommended **derating**	0.6 x rated power.				

- Features of precision wirewound resistors

- Higher precision and more tightly controlled TCR

- More stable

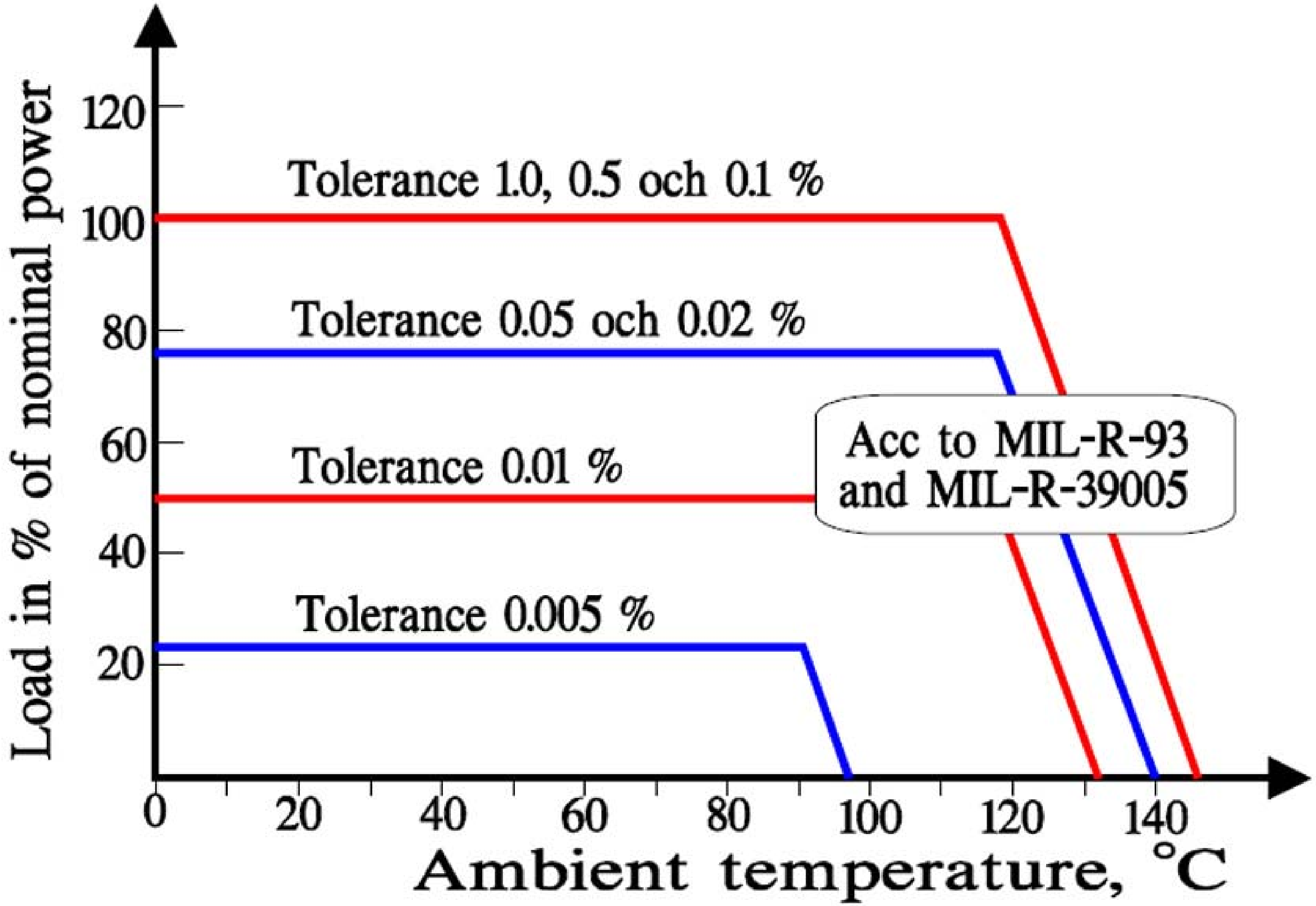
- For compact designs, metal film resistors with similar characteristics are used.

- Linear PTC resistors

- Low-value current sensing SMT current sensing resistors: 0.005 Ω, 0.25 – 2 W

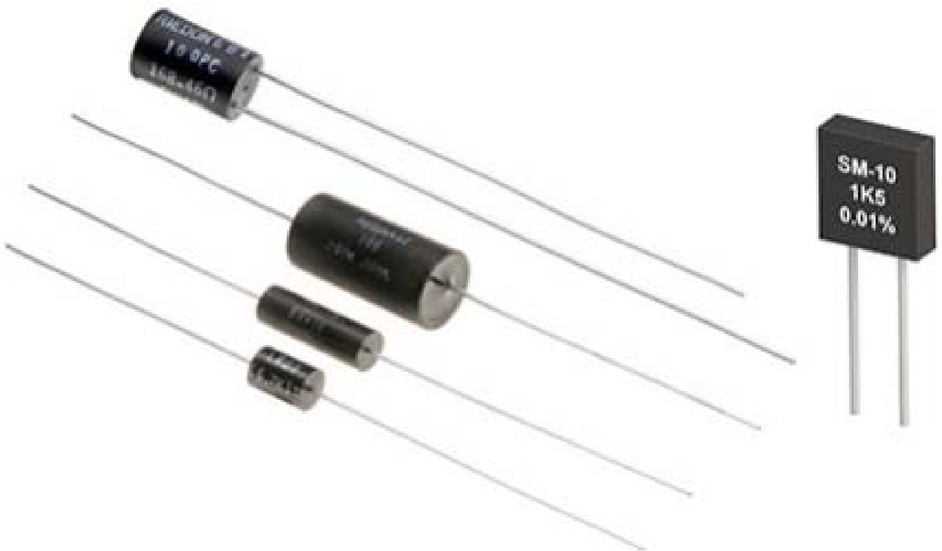
- Medical and industrial instrumentation: high-precision, high-power leaded resistors

- Tolerance vs loading in precision wirewound resistors



Precision wirewound resistors

- Riedon precision wirewound resistors
- R ±0.005%, TCR ±2 ppm/°C, 100 ppm/year
- Matched resistance sets: ±0.001%, ±0.5 ppm/°C



Characteristics of precision wirewound resistors

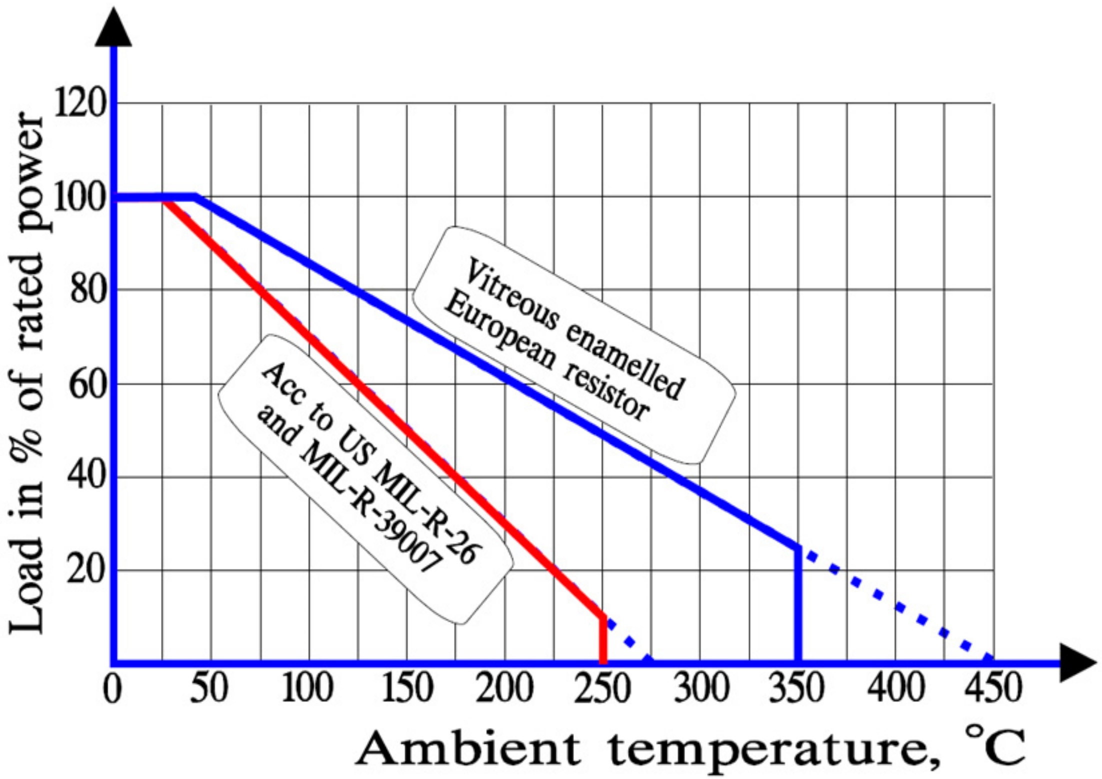
CHARACTERISTIC / DESCRIPTION		DATA / COMMENTS
Resistance	(Ω)	0.1···20M
Power	(W)	0.1···2.5
Tolerance	(±%)	0.005···2
Temperature range	(°C)	-55···+145
Limiting (maximum) voltage	(V)	150···1000
TC	(ppm/°C)	±2···±20
Stability:	(ΔR/R, ±%)	IEC Type 1: < 0.25
Noise	(μV/V)	Negligible: < 0.1
Voltage dependence	($x10^{-6}$/V)	Negligible: < 1
Frequency range		≤ 50 kHz.
Most common **failure mode**		**Open circuit.** Increasing failure rate when wire diameter, Φ, <0.1mm. Moisture + DC operation results in great corrosion risk (that is amplified by impurities in protecting lacquer). Connections between resistor wire and terminals are especially exposed.
Recommended **derating**		0.6 x rated power

- Wirewound resistors for power applications

- Designed to dissipate power

- High operating temperatures, limited stability

- Temperature derating is required.



Wirewound resistor products example

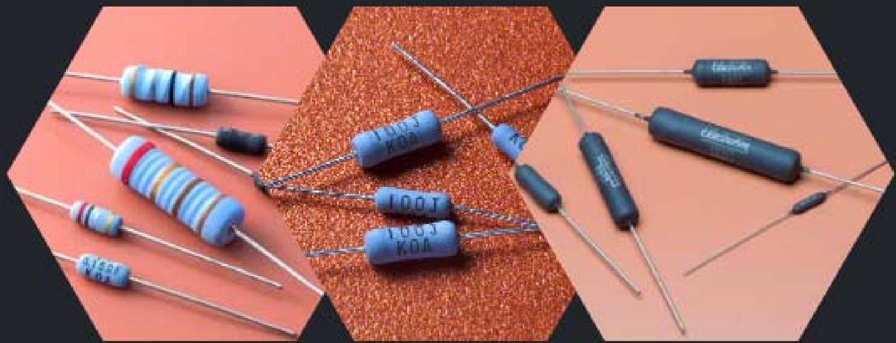
KOA SPEER ELECTRONICS, INC.

PRODUCTS APPLICATIONS RESOURCES SALES ABOUT US SEARCH

HOME › PRODUCTS › LEADED RESISTORS › WIREWOUND LEADED

Wirewound Leaded

Leaded Resistors



CWFS Coat Insulated Wirewound Resistor with Fusing Function

- Fail-safe mains fusing at AC 250V (CWFS23: 4.7 ~ 9.1: AC 200V)
- Flameproof retardant coating
- Power rating: 3W, 5W
- Fusing power: 90W, 150W
- Fusing time: 30 S. Max

CW Coat Insulated Wirewound Resistor

- Flameproof silicone coating equivalent (UL94V0)
- CW1SS- UL1412 approval (file No. E320246)
- CW_X - power type & CW_S - small type available
- Power rating: 0.25W, 0.5W, 1W, 2W, 3W, 5W
- Resistance range: 0.1 ~ 390Ω

CWH Miniature Wirewound Leaded Resistor

- Meets MIL-PRF-26 (U characteristics)
- High precision resistor with TCR ±20, ±50ppm/°C
- Power rating: 1W, 2W, 3W
- Resistance range: 0.1 ~ 3kΩ

▪ References on wirewound resistors

- DOEET: Construction and types of wirewound resistors

https://www.doeeet.com/content/eee-components/construction-and-types-of-wirewound-resistors/

5. Thick-film Resistors

- Thick-film resistors:

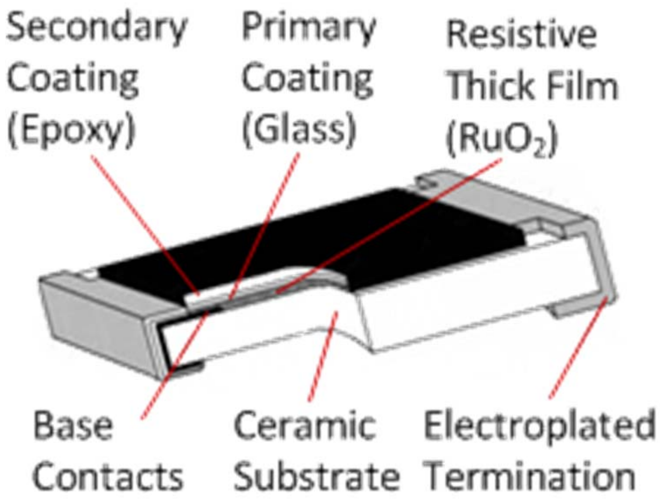
- Special metallic paste is fired onto an insulating substrate: 10-25 um

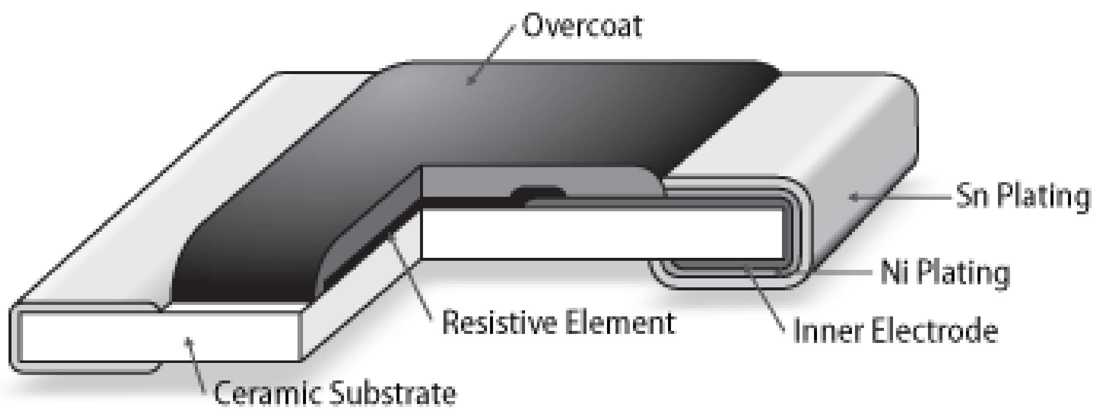
- Most widely used, most widely available, lowest cost

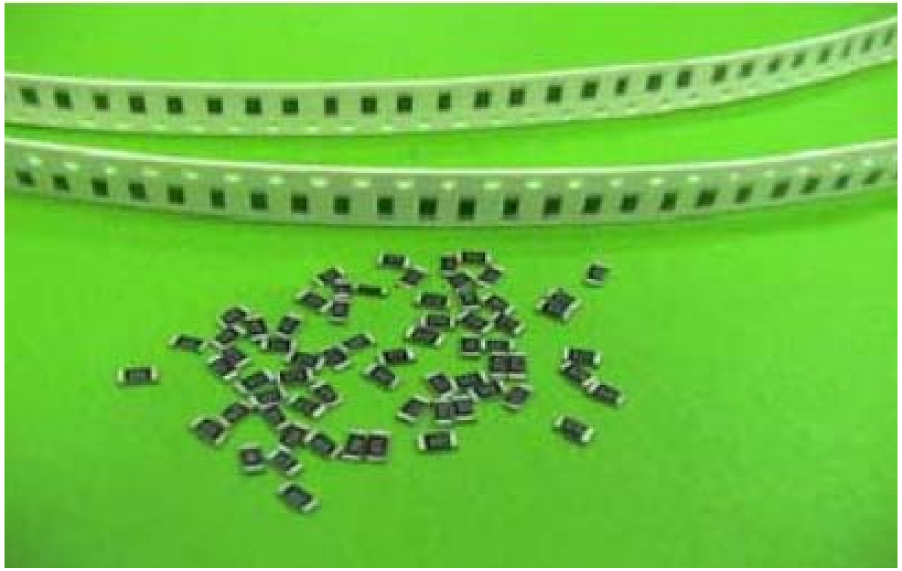
- For applications that don't require low TCR or tight tolerance

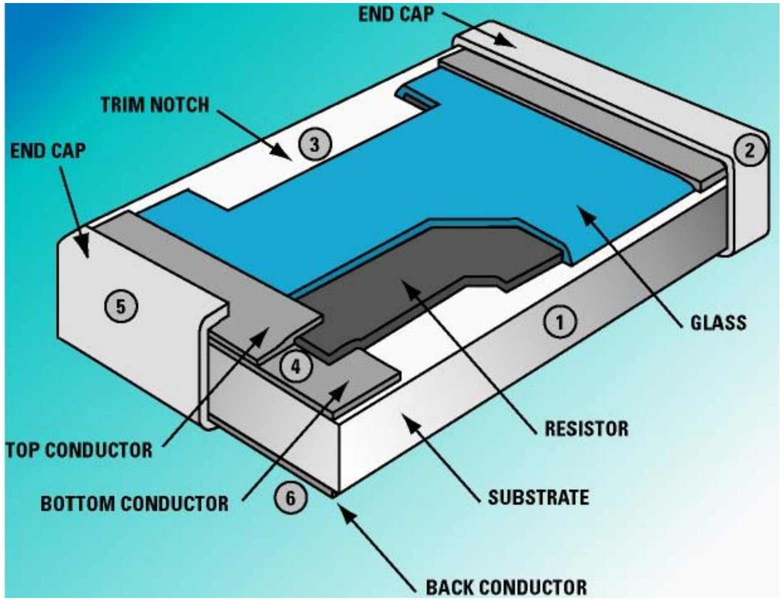
- Applications: consumer, industrial, telecom, automotive (AEC-Q200 compliant chip resistors only)

- Thick-film resistors construction and products packaging









- Film resistor resistance design:

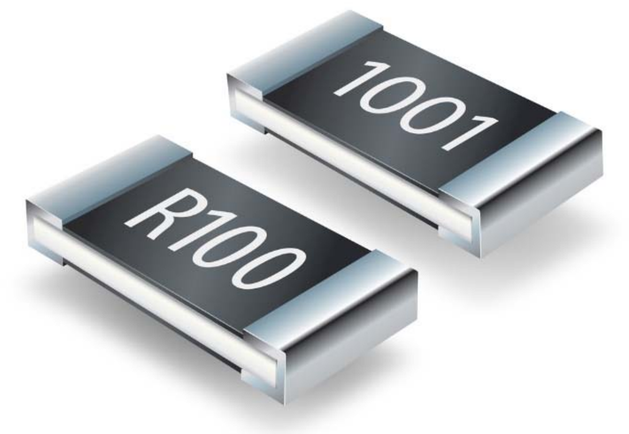
$$R = \rho \frac{L}{tW}$$

L : film length along current flow direction

ρ: reistivity of resistor material

t : film thickness

W : film width normal to current flow



- Ratings vs chip size

Chip Size	Power Rating	Voltage Rating
0201	50mW	25V
0402	63mW	50V
0603	100mW	75V
0805	125mW	150V
1206	250mW	200V

- Major manufacturers

- AVX, Vishay, Panasonic, Rohm, Yageo, KOA Seeper, Bourns, TE Connectivity

- High-temperature thick-film chip resistors

- Up to 200°C with temperature stability

- High voltage resistors

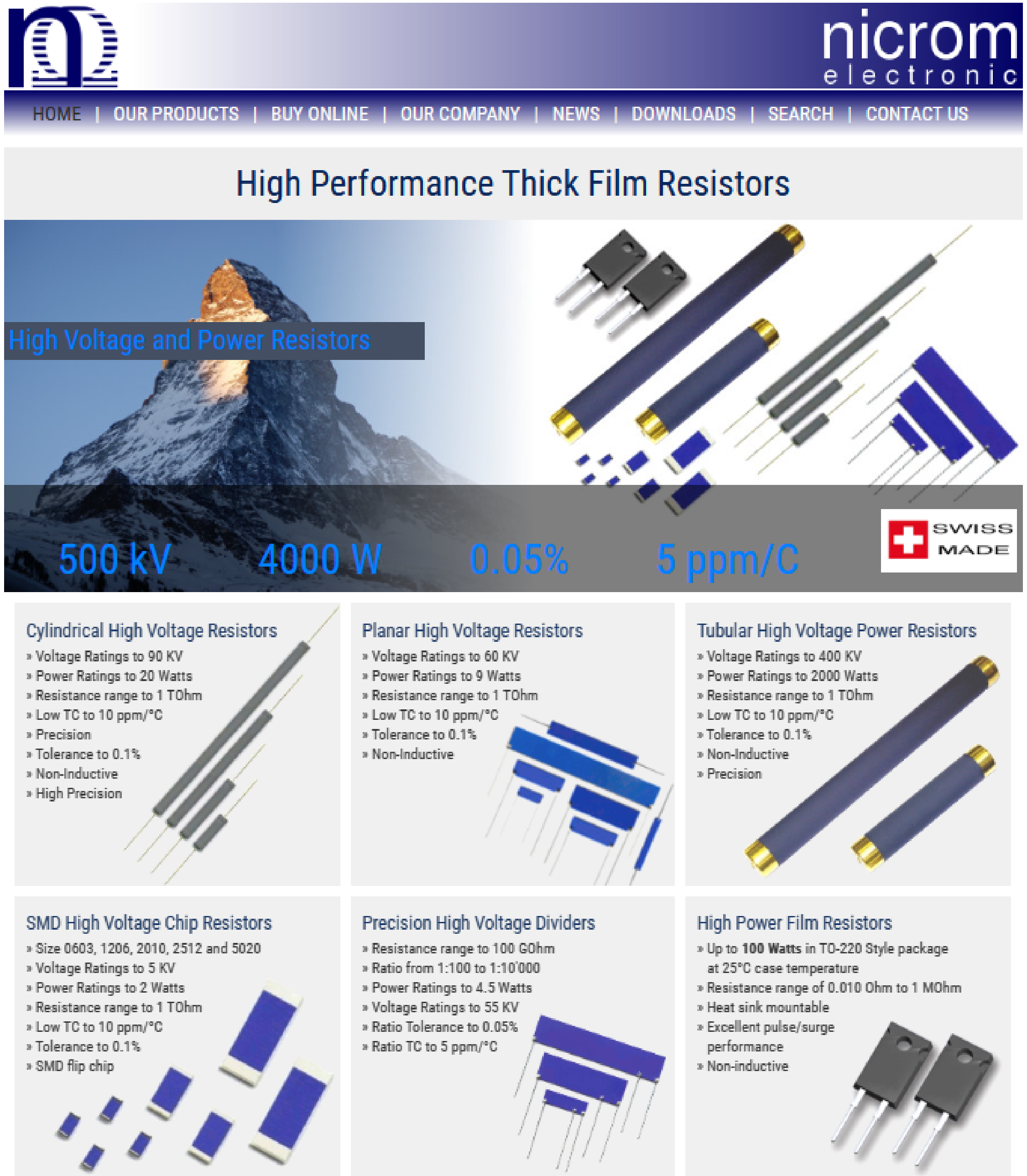
- Shapes: cylindrical, planar, tubular, SMD

- Precision high voltage dividers

- High power film resistors

- Heat sink mountable TO-220 package

- Thick-film resistor products example



- References on thick-film resistors

- Nicrome Electronic, www.high-votage-resistors.com

- Omite, www.ohmite.com/thick-film/

- Venkel, https://www.venkel.com/resistors

6. Thin-film Resistors

- Thin-film resistors:

- Metallic film (NiCr) is vacuum-deposited by sputtering processes on an insulating substrate

- Film thickness: 50-250 Angstroms (1Å = 10^{-8}cm = 0.1nm)

- Limited surge capabilities with respect to ESD, short-time overload

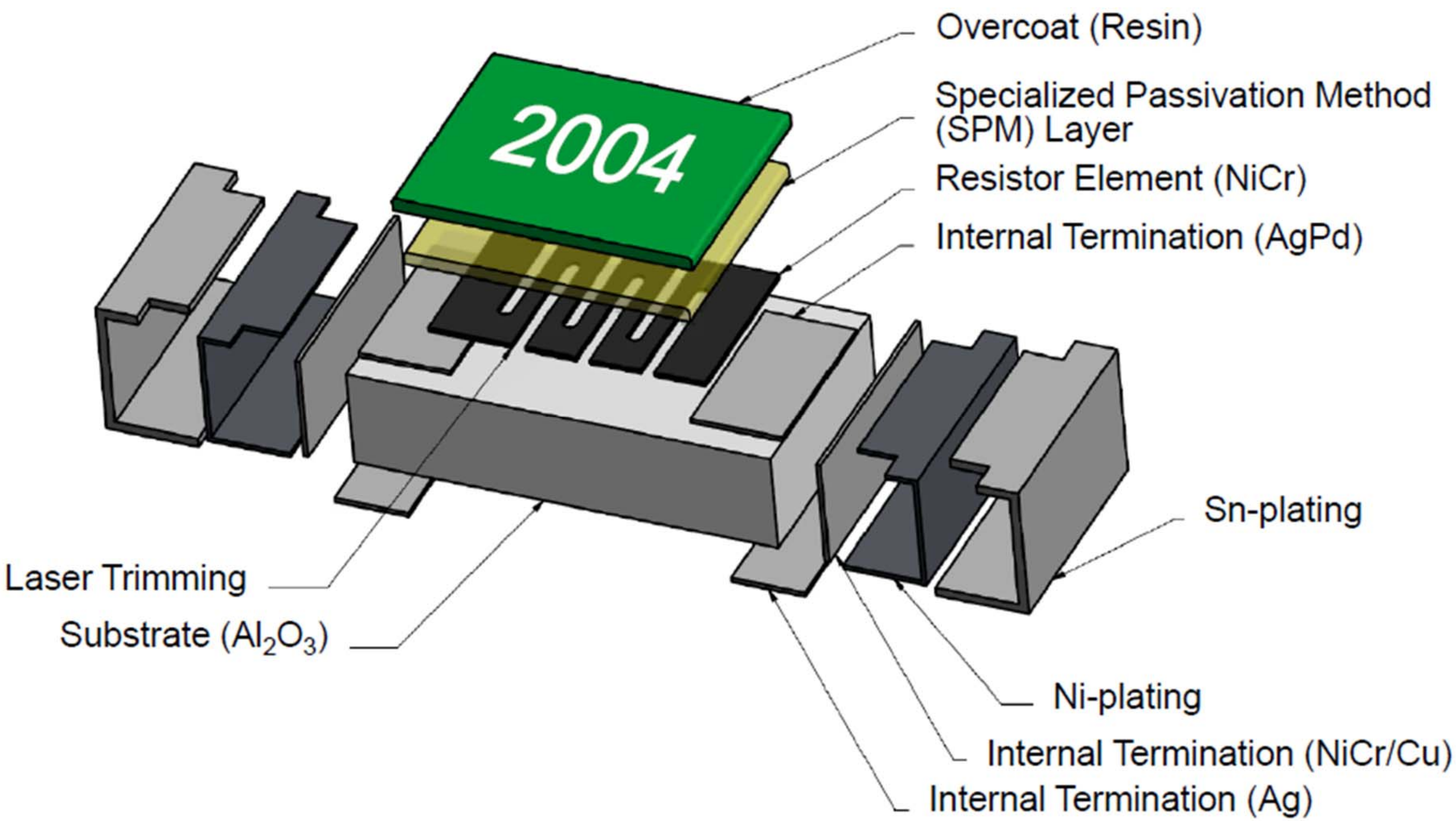
- More accurate, more stable, less change with temperature

- Lower noise, lower parasitic inductance and capacitance

- Higher cost

- Used for applications that require high stability, high accuracy, or low noise test instruments, medical and audio applications, precision control

- Detailed structure of thin-film resistors:



Source: Vishay

Chip resistor resistance code

3-digit code: $721=72\times10^1=720$, 4R7=4.7, R12=0.12

4-digit code: $7201=720\times10^1=7200$, R102=0.102, 11R5=11.5

EIA-96 code: $01Y=100\times0.01=1$, $52D=340\times1000=340k$

Código	Multiplicador
Z	0.001
Y or R	0.01
X or S	0.1
A	1
B or H	10
C	100
D	1000
E	10000
F	100000

Código	Valor	Código	Valor	Código	Valor	Código	Valor
01	100	25	178	49	316	73	562
02	102	26	182	50	324	74	576
03	105	27	187	51	332	75	590
04	107	28	191	52	340	76	604
05	110	29	196	53	348	77	619
06	113	30	200	54	357	78	634
07	115	31	205	55	365	79	649
08	118	32	210	56	374	80	665
09	121	33	215	57	383	81	681
10	124	34	221	58	392	82	698
11	127	35	226	59	402	83	715
12	130	36	232	60	412	84	732
13	133	37	237	61	422	85	750
14	137	38	243	62	432	86	768
15	140	39	249	63	442	87	787
16	143	40	255	64	453	88	806
17	147	41	261	65	464	89	825
18	150	42	267	66	475	90	845
19	154	43	274	67	487	91	866
20	158	44	280	68	499	92	887
21	162	45	287	69	511	93	909
22	165	46	294	70	523	94	931
23	169	47	301	71	536	95	953
24	174	48	309	72	549	96	976

Thin-film resistor products example

Thin film high precision resistor, very accurate resistor for tight tolerance down to 0.01% and Extremely low TCR 1ppm with advanced thin film technology. Wide resistance range and Anti-corrossive, anti-sulfur, automotive, AEC-Q200 qualified.

Precision Chip Resistor (AR Series)

Thin film NiCr accurate resistor, Size from 0201 to 2512, Tight tolerance 0.01% , 0.1% Low TCR 1ppm-50 ppm, 1-3Mohm resistance range for critical product designs. High power , High reliable ,High Stability , high

High Frequency (up to 40GHz) Thin Film Precision Chip Resistor (ARF Series)

ARF series chip resistors are designed with low internal reactance. The thin film technology applied to resistors is appropriated to reduce the parasitic inductance and capacitance. Low internal reactance allows these

General Purpose Thin Film Resistor (ARG Series)

Thin film NiCr resistor, Size from 0402-1206, 0.1% , low TCR 25-50ppm , Wide range of 1ohm-3Mohm, General purpose for accurate resistor, Low cost and good performance. Wide applications for various

- Thin-film resistor vs thick-film resistor

Characteristic	Thin Film	Thick Film
Example	 *While the manufacturing process and properties are very different, the chip resistors for thin and thick film often have a similar appearance.*	
Construction		
Film thickness (μm)	±0.1	±100
Manufacturing process	Sputtering (Vacuum Deposition)	Screen and stencil printing
Trimming	Abrasive or Laser, for complex patterns photo etching	Abrasive or Laser
Resistive Material	Uniform metallic film, usually Nichrome	Paste of Ruthenium Oxide or other alloy.

- Thin-film resistor vs thick-film resistor

Properties		
Resistance Values (Ω)	0.2 – 20M	1 – 100M
Tolerance (%)	±0.1 - ±2	±1 - ±5
Temperature Coefficient (ppm/K)	±5 - ±50	±50 - ±200
Maximum Operating Temperature (°C)	155	155
Maximum Operating Voltage Umax (V)	50 - 500	50 – 200

Thin-film resistor vs thick-film resistor

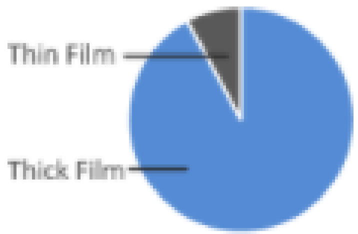
Non-linearity (dB)	>110	>50
Current Noise (μV/V)	<0.1	<10
Power Rating P_{70} (W)	1/16 – 1	1/16 – 1/4
Stability at P_{70} (1000h) ΔR/R %	±0.15 - ±0.5	±1 - ±3
Moisture resistance	Thick film is more resistant to moisture, since they are glass like.	
High frequency behavior	Thin film features lower parasitic inductance and capacitance. However, inductance may be high if thin film is executed with a cylindrical shape that is spiral cut.	

- Thin-film resistor vs thick-film resistor

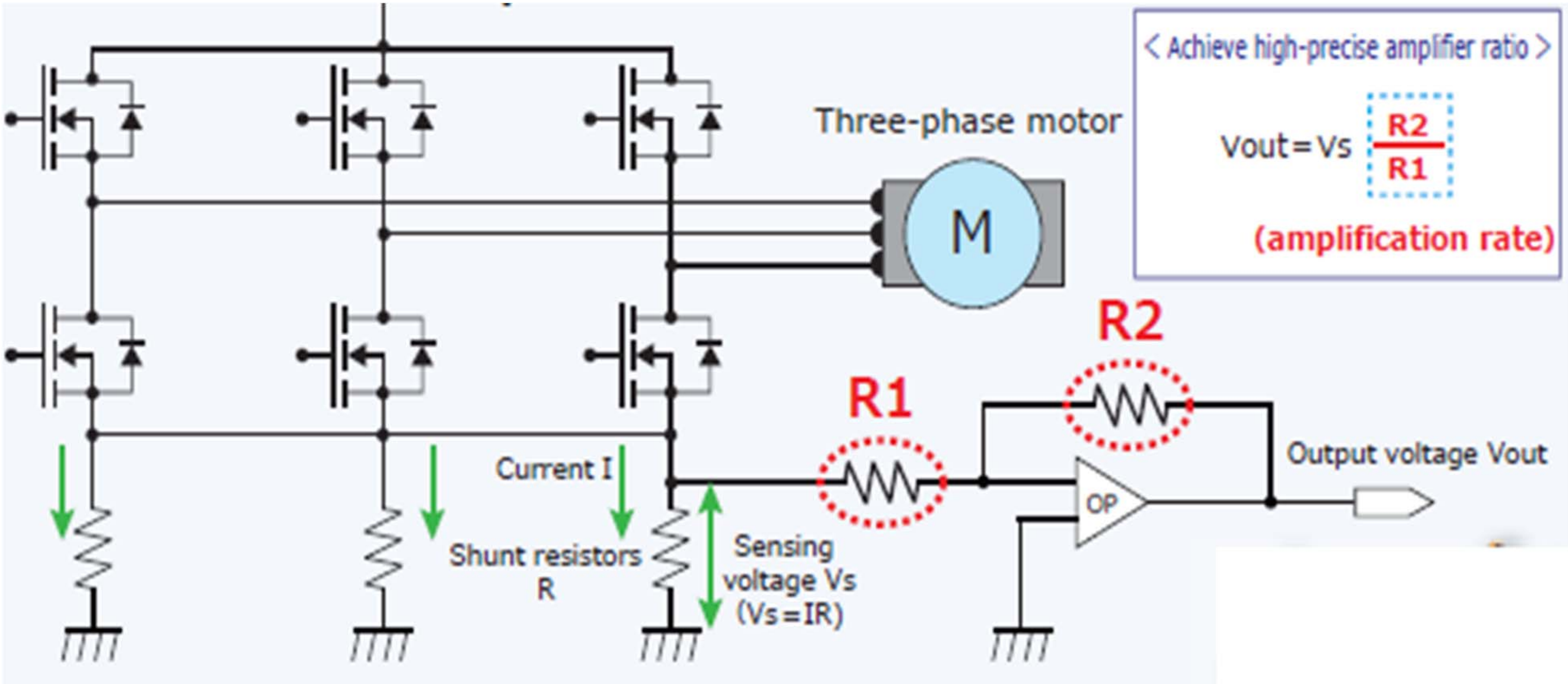
Applications

Typical areas of use	High precision: Measuring or monitoring equipment, medical or audio applications, precision controls.	Very wide, almost any electrical device with battery or AC connection. The average PC contains well over 1000 thick film chip resistors.

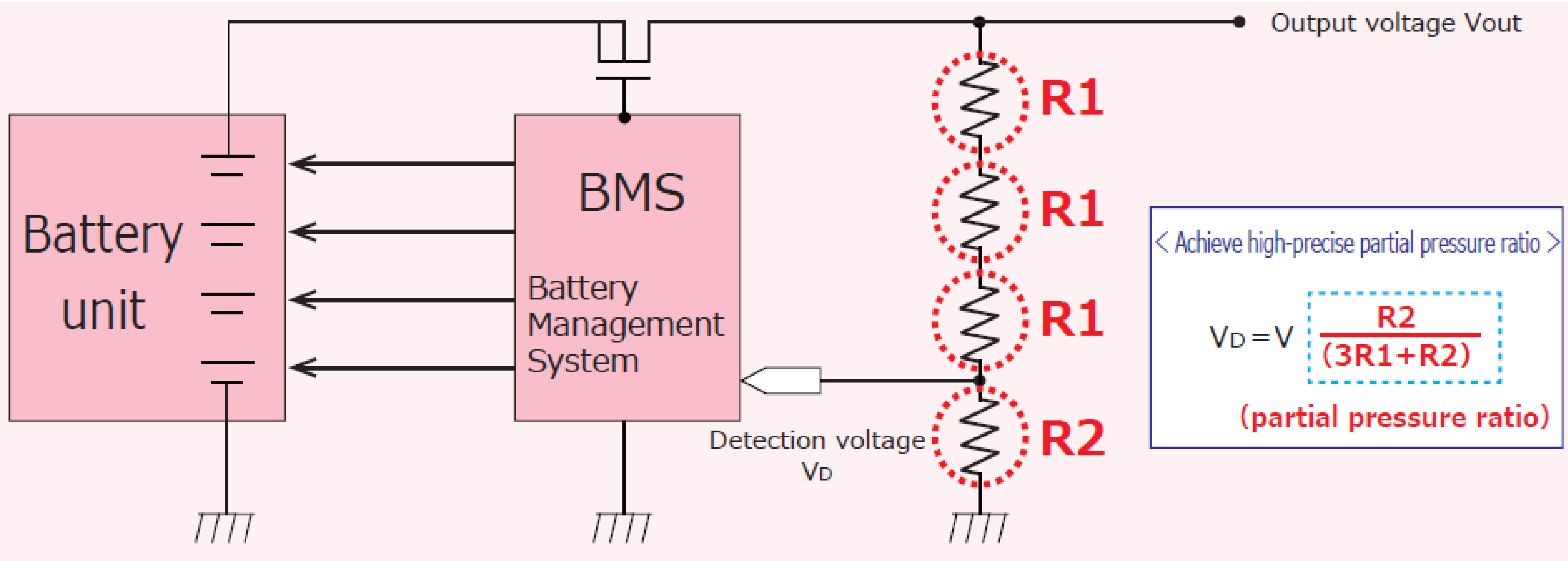
Market share

Cost	More expensive than thick film.	Lowest cost resistor type on the market. Preferred solution if performance requirements are low.
Estimated use in analogue circuits		

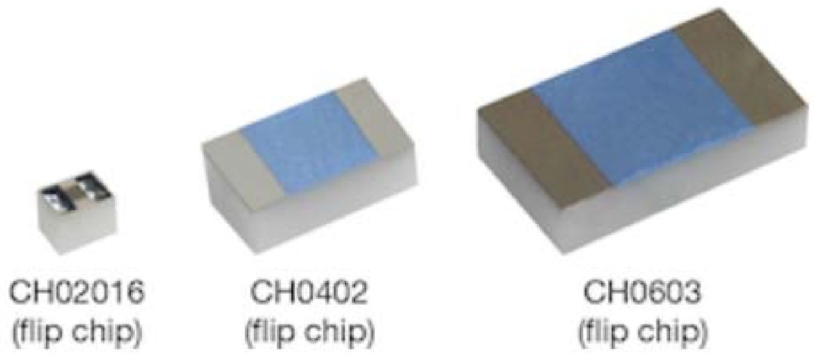
- Precision thin-film resistor application, current detection



- Precision thin-film resistor application, voltage detection

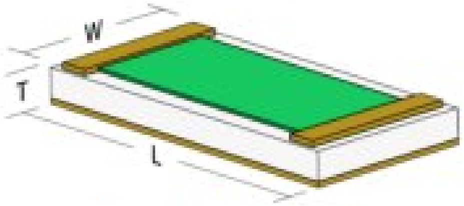


- Example: Vishay 70-GHz thin-film chip resistors



- Example: Epak Electronics 40-GHz thin-film chip resistors

MSMW

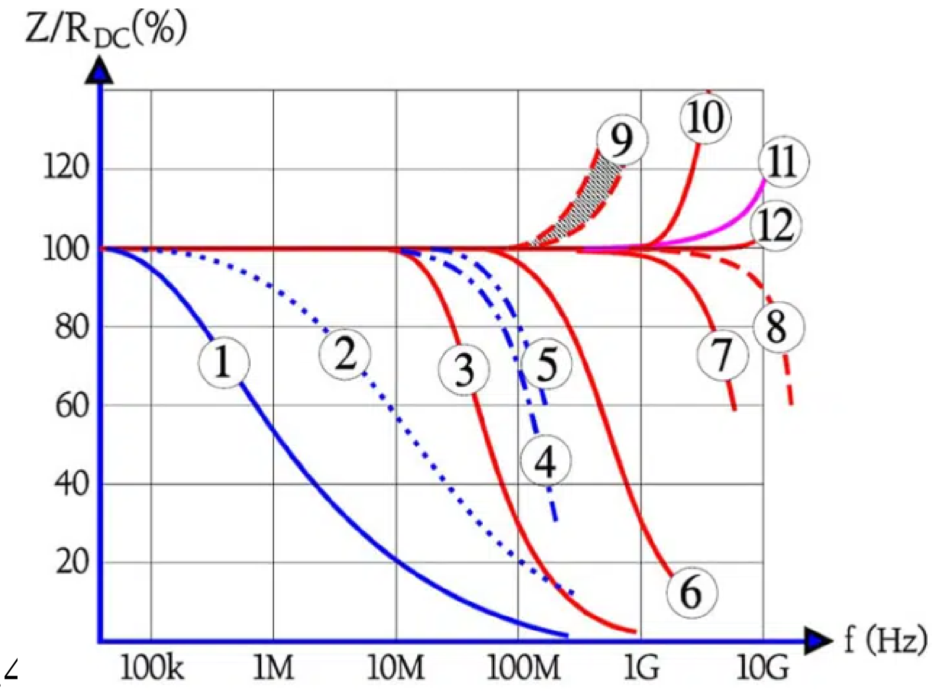


Wire bondable gold
OR Solderable gold with nickel barrier
OR Nickel barrier pre-soldered

SERIES	LENGTH	WIDTH	THICKNESS	TOLERANCE	VALUE	POWER RATING @70°C
MSMW110	0.040"	0.020"	0.010"	(+/-0.003")	2 to 18K	125mw
MSMW112	0.050"	0.050"	0.010"	(+/-0.003")	10 to 3K	125mw
MSMW115	0.050"	0.025"	0.010"	(+/-0.003")	2 to 800	125mw
MSMW118	0.021"	0.017"	0.010"	(+/-0.003")	2 to 300	125mw
MSMW120	0.100"	0.050"	0.010"	(+/-0.003")	5 to 250	125mw
MSMW121	0.100"	0.100"	0.010"	(+/-0.003")	3 to 3K	500mw
MSMW122	0.020"	0.016"	0.010"	(+/-0.003")	2 to 300	125mw
MSMW124	0.150"	0.085"	0.010"	(+/-0.003")	25 to 400	500mw

7. Resistor Frequency Characteristics

- Ref: www.passive-components.eu



1: Carbon composite, 1/4W, 1MΩ

2: Carbon composite, 1/4W, 100kΩ

3: Thick-film chip, EIA 0603, 100kΩ

C=0.05pF, L=0.4nH

4: Metal film, DIN 0207, 100kΩ, C=0.4pF

5: MELF, DIN 0204, 10kΩ

6: Thick-film chip, EIA 0603, 10kΩ, C=0.05pF, L=0.4

Metal-foil chip, EIA 1210, 10kΩ

7: Thick-flim chip, EIA 0603, 1kΩ, C=0.05pF, L=0.4nH

8: MELF, DIN 0102, 10Ω, C=0.035pF, L=0.8nH

9: MELF, DIN 0204, 10Ω

10: Thick-film chip, EIA 0603, 10Ω, C=0.05pF, L=0.4nH

11: Thin-film chip, EIA 0603, 100Ω, C=0.035pF, L=1.2nH

12: Thick-film chip, EIA 0603, 100Ω, C=0.05pF, L=0.4nH

7. Resistor Frequency Characteristics

- Ref: Chen, IEEE, 2020

- 120-Ω SMD resistor, 0402

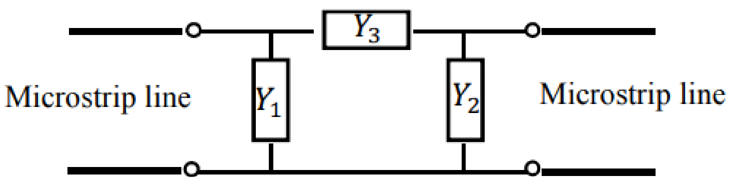


Fig. 1. General π-type equivalent circuit model

$$Y_1 = \frac{D-1}{B}\ ,\ Y_2 = \frac{A-1}{B},\ Y_3 = \frac{1}{B}$$

$$A = \frac{(1+S_{11})(1-S_{22})+S_{12}S_{21}}{2S_{21}}\ ,$$

$$B = \frac{(1+S_{11})(1+S_{22})-S_{12}S_{21}}{2S_{21}}Z_0$$

$$D = \frac{(1-S_{11})(1+S_{22})+S_{12}S_{21}}{2S_{21}}\ .$$

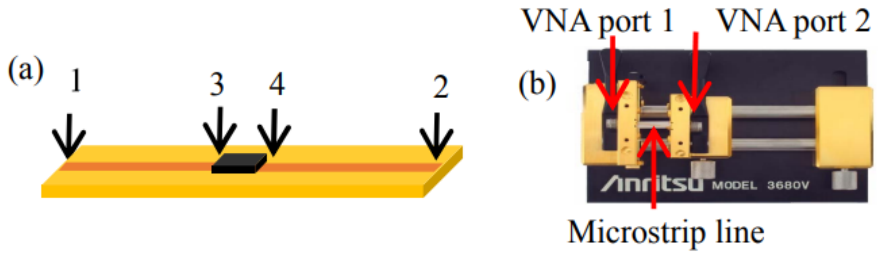


Fig. 2. (a) Lumped element in microstrip. (b) Microstrip loaded with lumped element in test fixture Anritsu 3680.

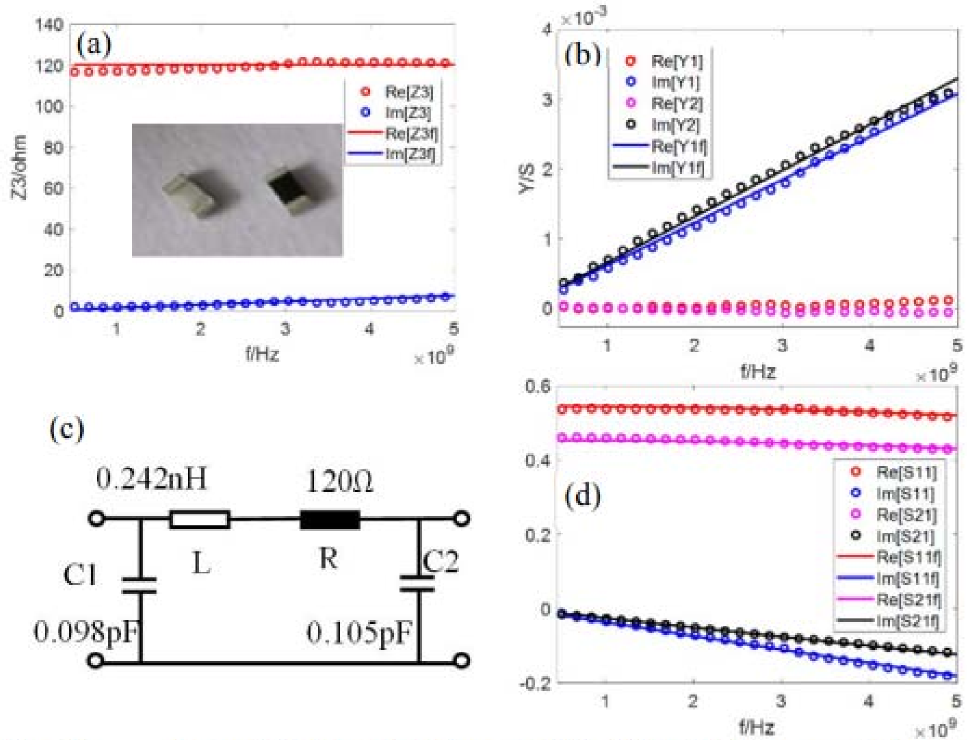
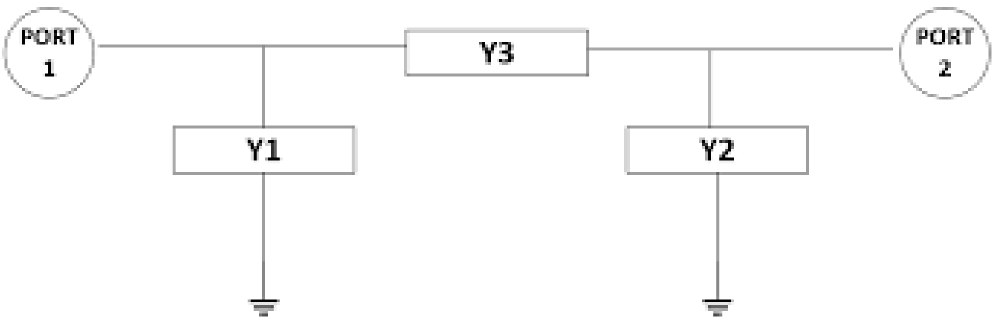


Fig. 3. (a) and (b) The admittance of Y1, Y2 and Y3 in general PI circuit model of SMD resister and their fitting curves. The impedance Z3 is 1/Y3. (c)The finalized circuit model of the SMD resistor. (d) The S-parameters comparison between the circuit model (S_{11}, S_{21}) and the experiment (S_{11f}, S_{21f}).

8. SMT Resistor Equivalent Circuit Modeling

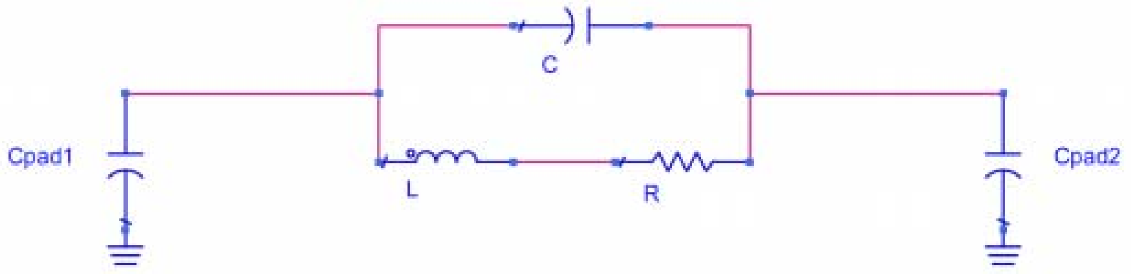
- pi-network model for SMT devices

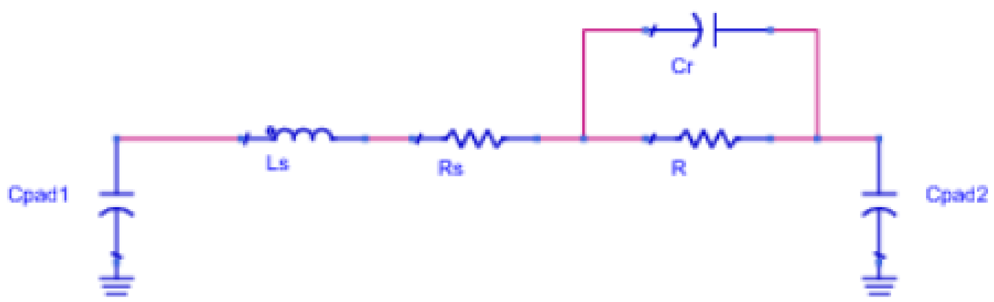


$$Y_{1i} = Y_1 + \frac{Y_3(Y_2 + Y_0)}{Y_3 + Y_2 + Y_0}, \; Y_{2i} = Y_2 + \frac{Y_3(Y_1 + Y_0)}{Y_3 + Y_1 + Y_0}$$

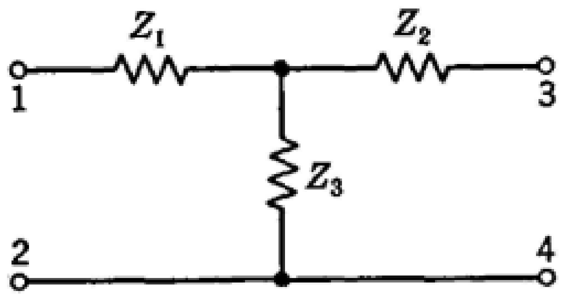
$$S_{11} = \frac{Y_0 - Y_{1i}}{Y_0 + Y_{1i}}, \; S_{12} = (1 + S_{22})\frac{Y_3}{Y_3 + Y_1 + Y_0}$$

$$S_{22} = \frac{Y_0 - Y_{2i}}{Y_0 + Y_{2i}}, \; S_{21} = (1 + S_{11})\frac{Y_3}{Y_3 + Y_2 + Y_0}$$

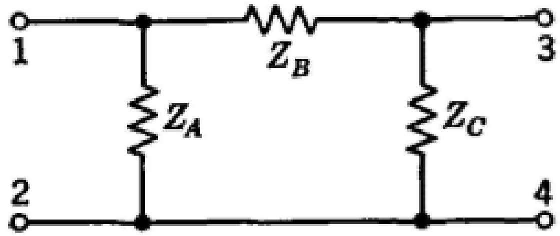




- Pi network and T-network conversion



T section



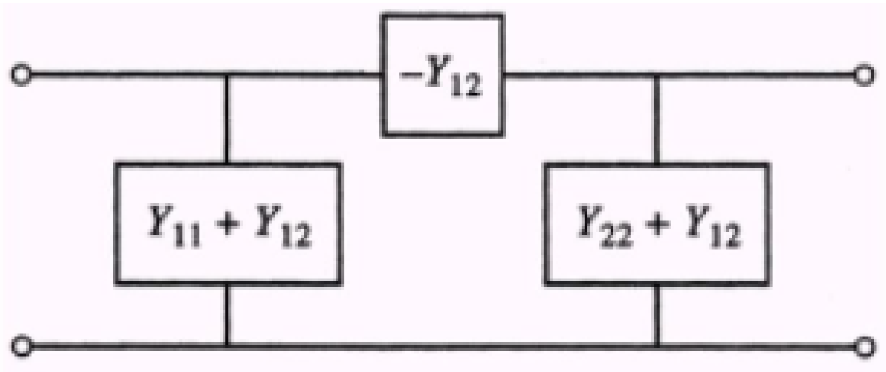
π section

$$Z_1 = \frac{Z_A Z_B}{D},\ Z_2 = \frac{Z_B Z_C}{D},\ Z_3 = \frac{Z_C Z_A}{D},\ D = Z_A + Z_B + Z_C$$

$$Z_A = \Delta / Z_2,\ Z_B = \Delta / Z_3,\ Z_C = \Delta / Z_1,\ \Delta = Z_1 Z_2 + Z_2 Z_3 + Z_3 Z_1$$

Admittance matrix

- Measure S_{11}, S_{12}, S_{21} (= S_{12}), S_{22} and extract Y_{11}, Y_{12}, Y_{21}(= Y_{12}), Y_{22}.



$$Y_{12} = Y_{21} = -Y_3,\ Y_{11} = Y_1 + Y_3,\ Y_{22} = Y_2 + Y_3$$

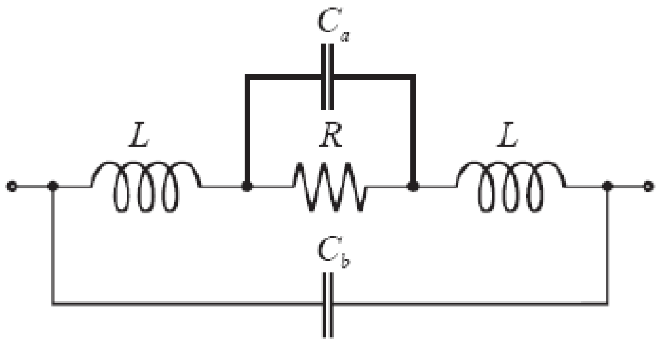
$$Y_1 = Y_{11} + Y_{12}, Y_2 = Y_{22} + Y_{12},\ Y_3 = -Y_{12}$$

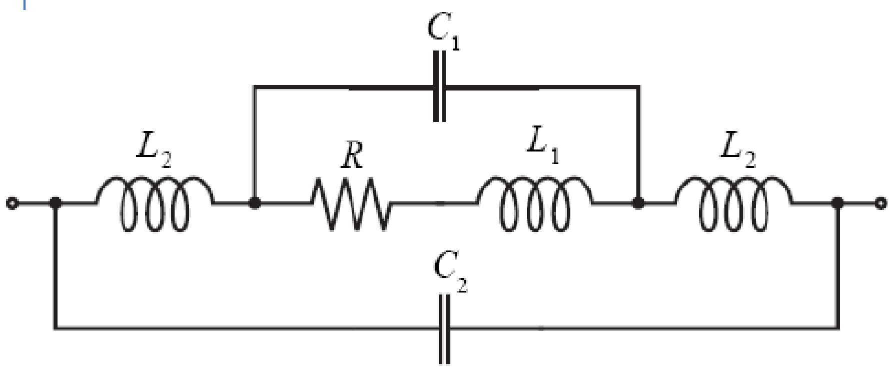
$$Y_{11} = Y_0 \frac{(1 - S_{11})(1 + S_{22}) + S_{12}S_{12}}{(1 + S_{11})(1 + S_{22}) - S_{12}S_{12}},\quad Y_{12} = Y_0 \frac{-2S_{12}}{(1 + S_{11})(1 + S_{22}) - S_{12}S_{12}}$$

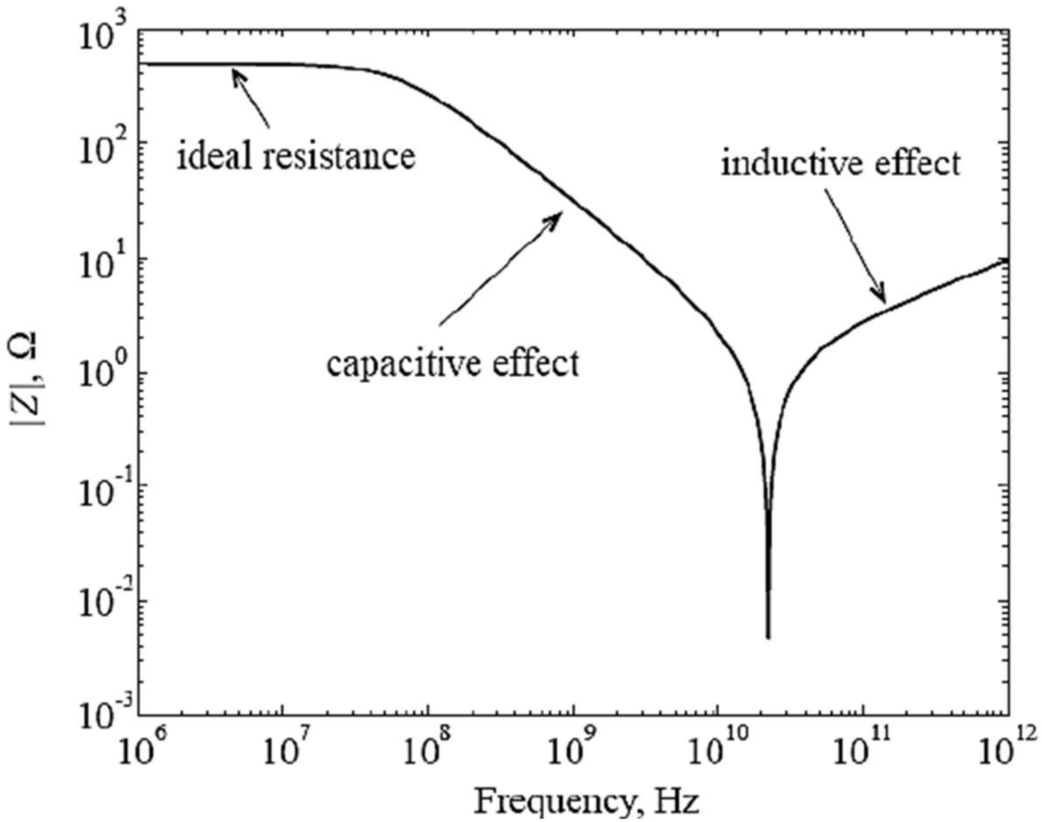
$$Y_{22} = Y_0 \frac{(1 + S_{11})(1 - S_{22}) + S_{12}S_{12}}{(1 + S_{11})(1 + S_{22}) - S_{12}S_{12}}$$

- Equivalent circuit models and frequency response

- Frequequency response example: 500-ohm thin-film resistor

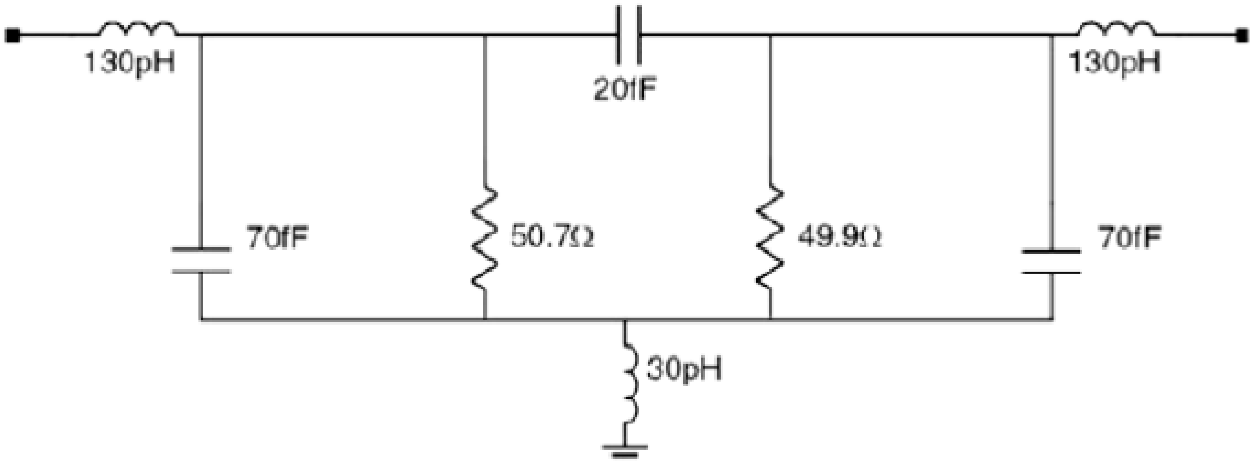




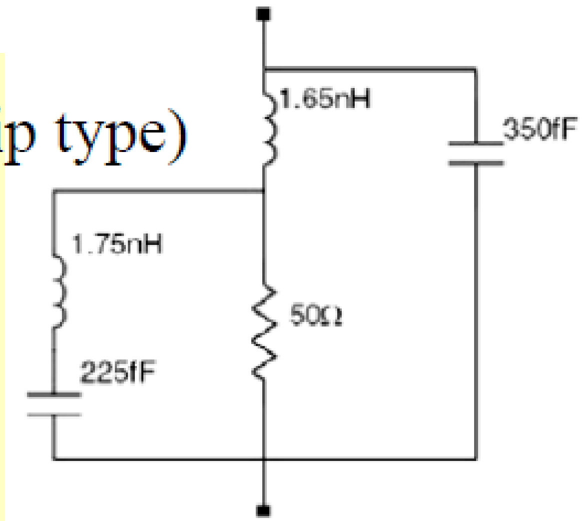


- Reistor equivalent circuit examples

CHC-CC0910B-xx-50R0-x (BGA type)



PFC-W0603HF-xx-50R0-x (0603 chip type)



- Resistor equivalent circuit example:

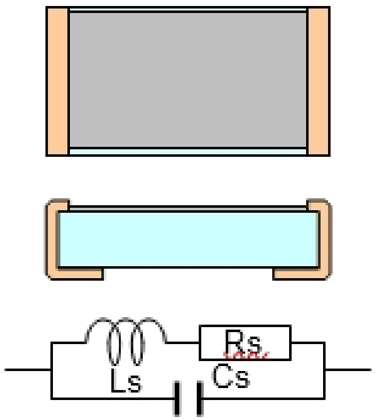


FIG 14. Microwave resistor, structure and equivalent circuit

model	power	feature	Res.	Cs	Ls
RFH52	10W	ALN chip	See note1	2.3pF	1.4nH
RFH72	20W	ALN chip	See note1	2.5pF	2.6nH
RFR010	10W	ALN chip	See note1	2.2pF	1.1nH
RFR020	20W	ALN chip	See note1	–	–
RFR050	50W	ALN chip	See note1	3.3pF	1.6nH
RFR100	100W	ALN chip	See note1	–	–
RFR150	150W	ALN chip	See note1	5.5pF	2.5nH
RFR250	250W	ALN chip	See note1	7.6pF	4.2nH

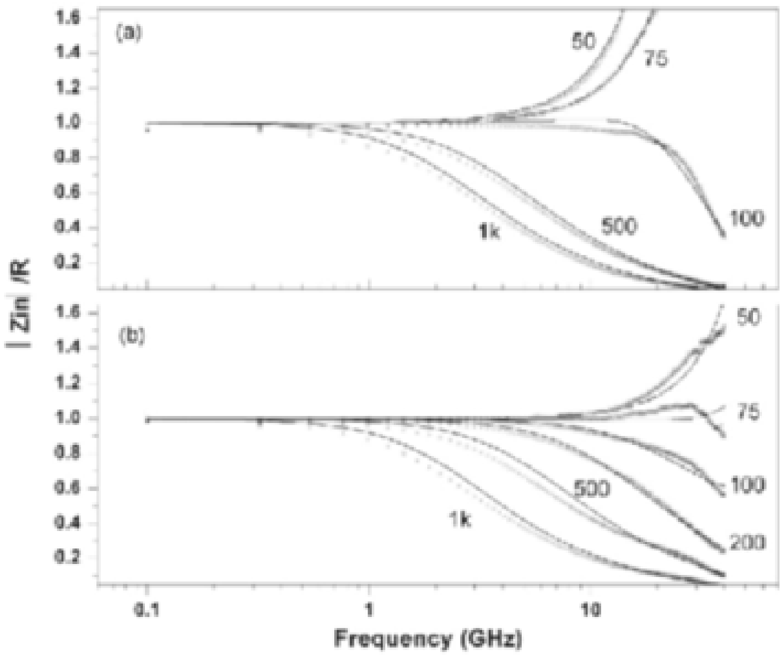
Note 1. 16.67, 50, 100, 150, 200, 250, 300, 400, 600, 800 ohm

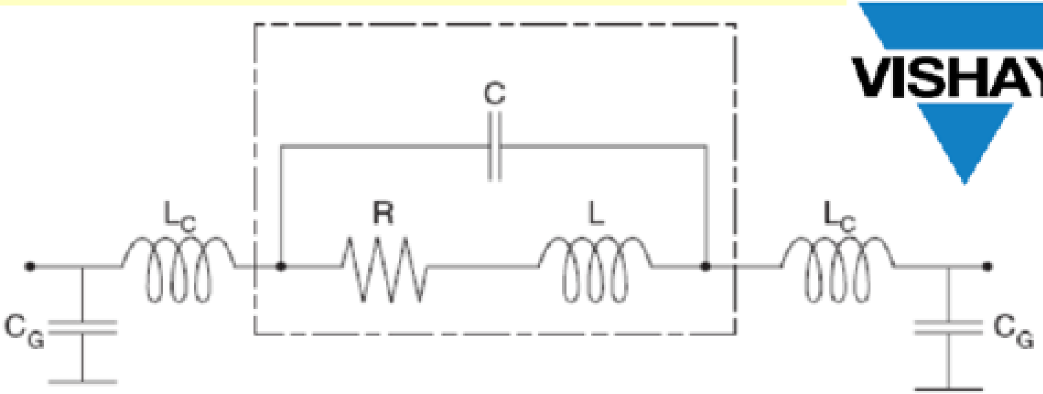
TABLE 5. Typical microwave resistors.

- Commercial thin-film chip resistors

TABLE 1 - PARAMETERS FOR DIFFERENT CASE SIZES UTILIZED

CASE SIZE	LENGTH (inch/ mm)	WIDTH (inch/ mm)	RESISTOR AREA ($inch^2$/ mm^2)	MODEL INTERNAL COEFFICIENTS C (pF)	MODEL INTERNAL COEFFICIENTS L (nH)
0201	0.02/ 0.51	0.01/ 0.25	0.00004/ 0.02581	0.0206	1.73×10^{-5}
0402	0.04/ 1.02	0.02/ 0.51	0.000352/ 0.22710	0.0262	1.89×10^{-3}
0402 (wrap)	0.04/ 1.02	0.02/ 0.51	0.000352/ 0.22710	0.0392	0.1209
0603	0.064/ 1.626	0.032/ 0.813	0.000816/ 0.52645	0.0403	0.0267





VISHAY

C: internal shunt capacitance

L: internal inductance

R: resistance

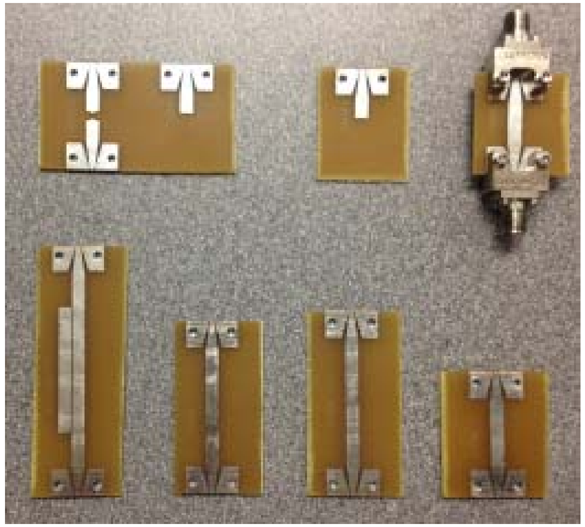
L_C: external connection inductance

C_G: external capacitance to ground

- Test fixture

- SMT component test fixture

- Fixture calibration: TRL method



- Scattering parameter measurements

- Fixture de-embedding (calibration)

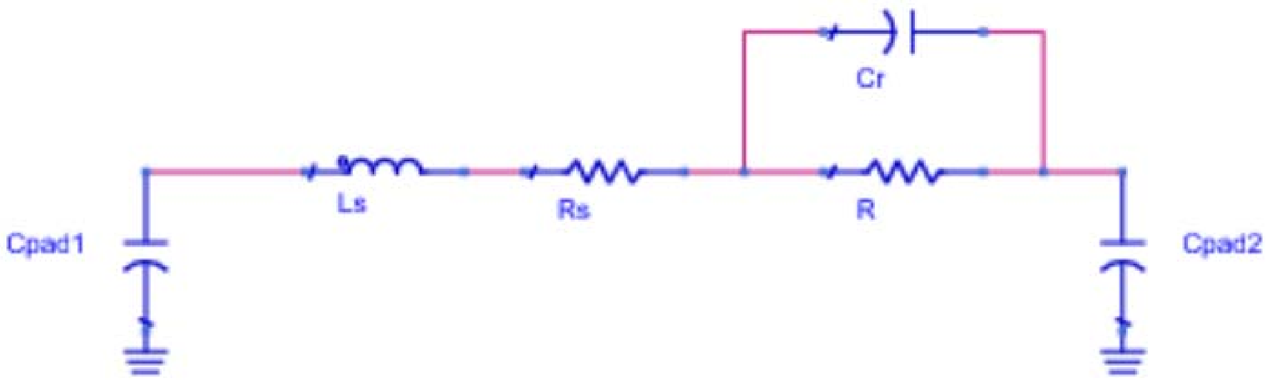
- S11, S21 vs frequency

- Come up with an equivalent circuit based on physical modeling

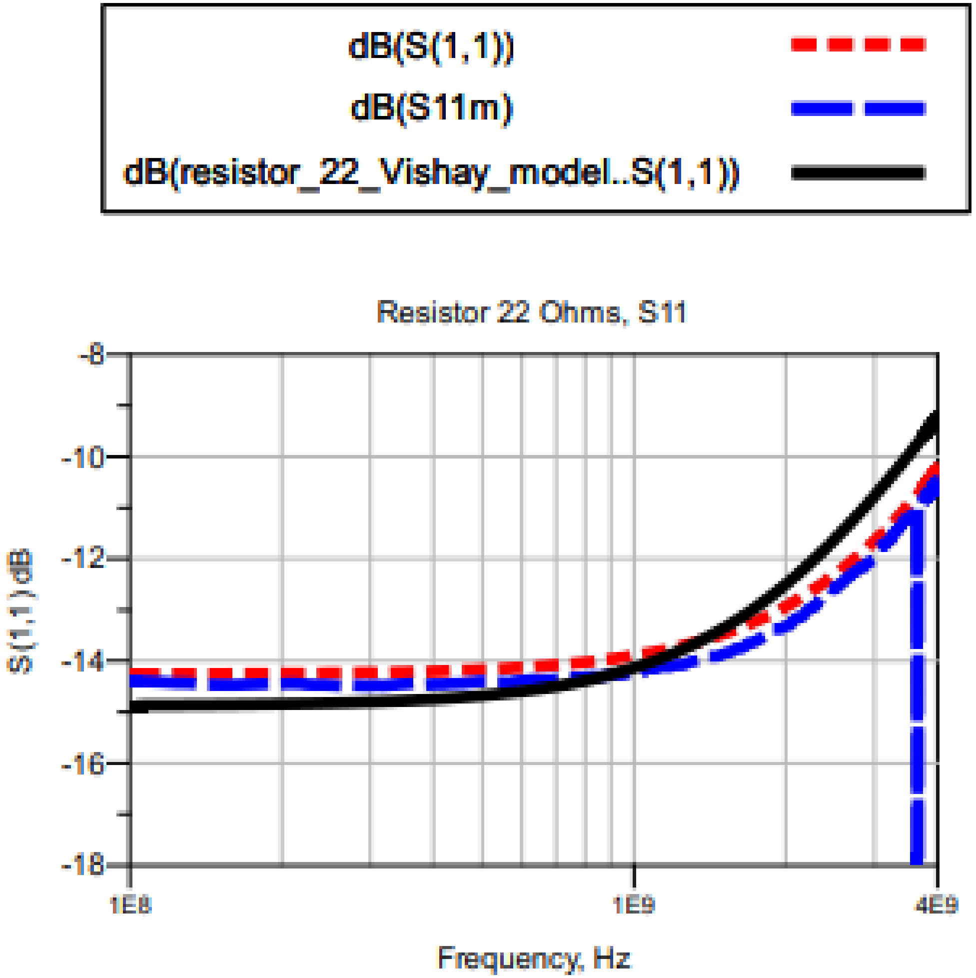
- Find element values by optimization over the measured frequency range

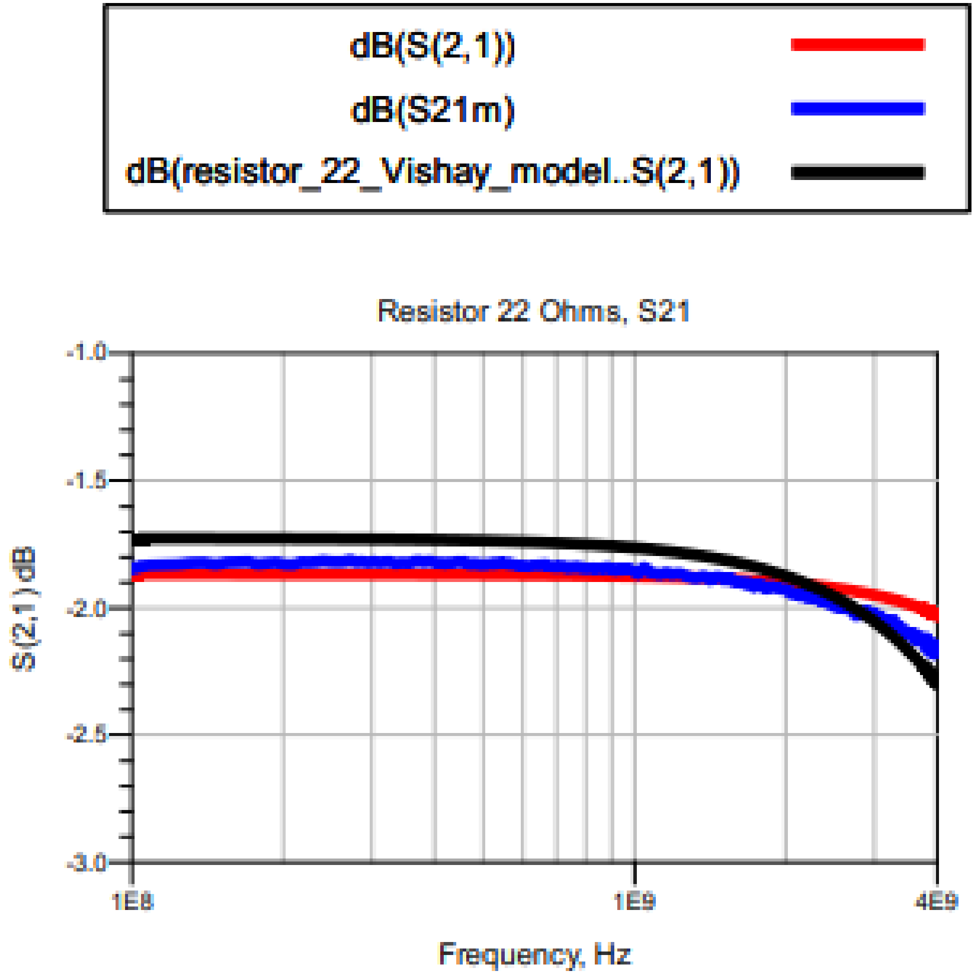
- Random walk, simulated annealing, gradient optimizer

- Example: 22-Ω SMT resistor

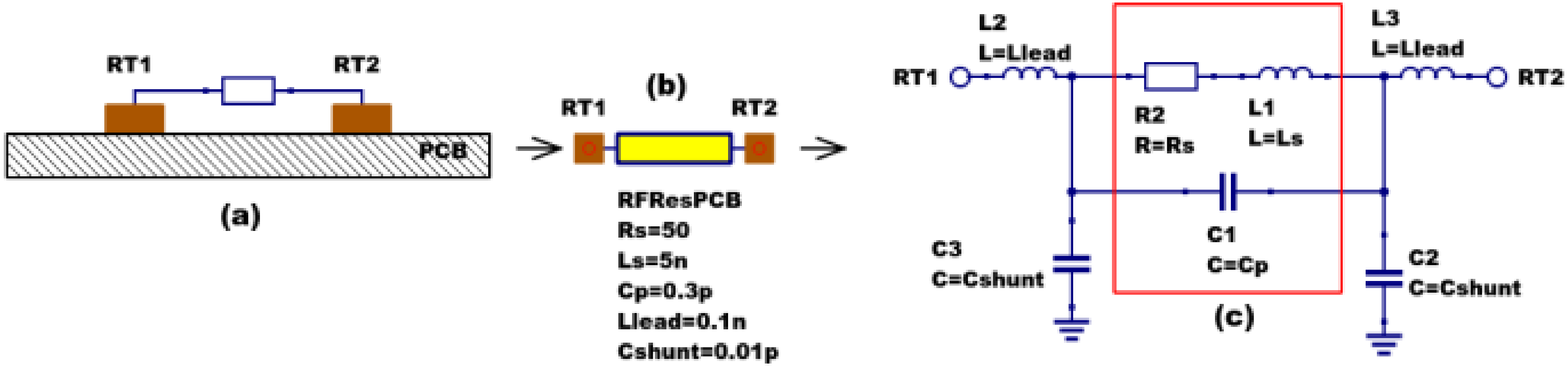


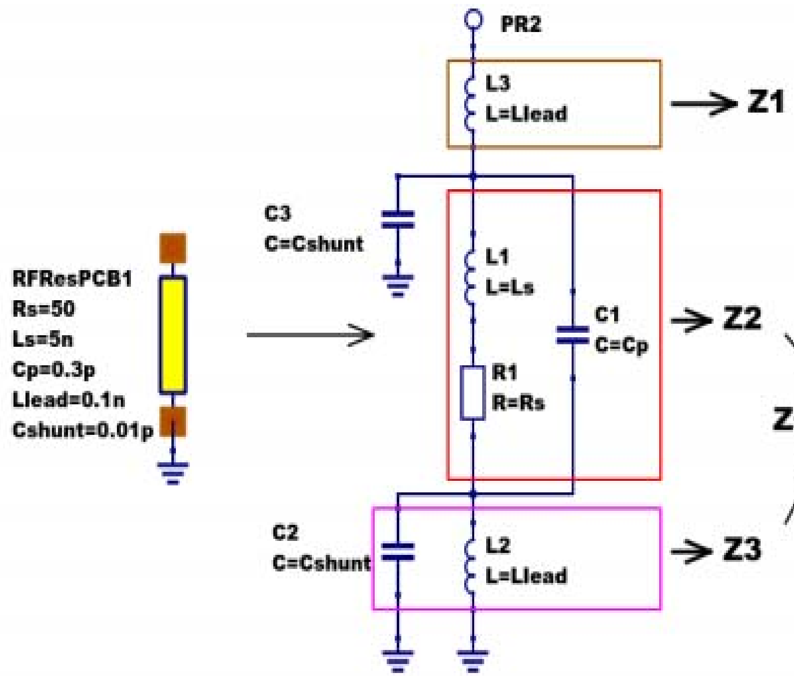
Resistor(Ω)	Rs(Ω)	Ls(nH)	Cr(pF)	Cpad1(pF)	Cpad2(pF)
Resistor 22 Ω					
23.24	0.49	2.61	0.18	0.15	0.15
24.19	0.19	2.49	0.10	0.16	0.14
23.50	0.49	0.20	0.53	0.12	0.10


dB(S(1,1))
dB(S11m)
dB(resistor_22_Vishay_model..S(1,1))
Resistor 22 Ohms, S11
-8
-10
-12
-14
-16
-18
S(1,1) dB
1E8
1E9
4E9
Frequency, Hz


dB(S(2,1))
dB(S21m)
dB(resistor_22_Vishay_model..S(2,1))
Resistor 22 Ohms, S21
-1.0
-1.5
-2.0
-2.5
-3.0
S(2,1) dB
1E8
1E9
4E9
Frequency, Hz

- Example: 47-Ω resistor using S11





Zseries = Z2 +Z3 → Zb = Zseries || 1/(j ·w ·Cshunt)

The RF resistor model impedance Z = Zb + Z1

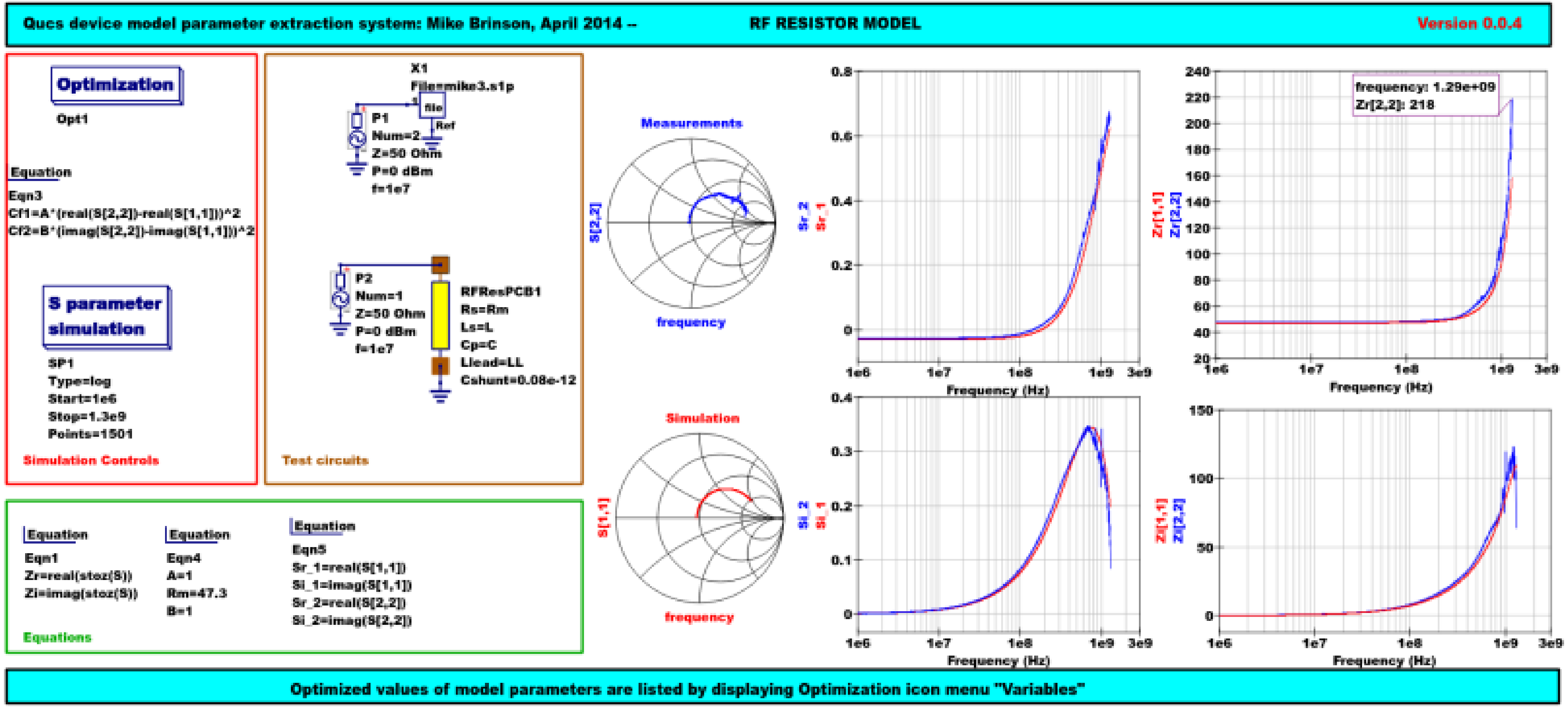


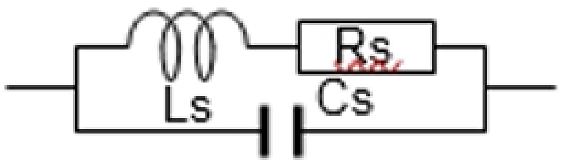
Figure 8: Qucs device model parameter extraction system applied to a nominal 47 Ω resistor represented by the subcircuit model illustrated in Figure 2 (c). Fixed model parameter values: Rs=Rm=47.3Ω, $CShunt$=0.08pF; Optimised values: Ls=L=10.43nH, $Llead$=LL=1.47nH, Cp=C=0.69pF. To reduce simulation time the ASCO cost variance was set to 1e-3. The ASCO method was set to DE/best/1/exp.

9. Coding Examples

- Example 1

Input:

- Resistor equivalent circuit values: example Rs = 100 Ω, Ls = 1.5 nH, Cs = 3.0 pF



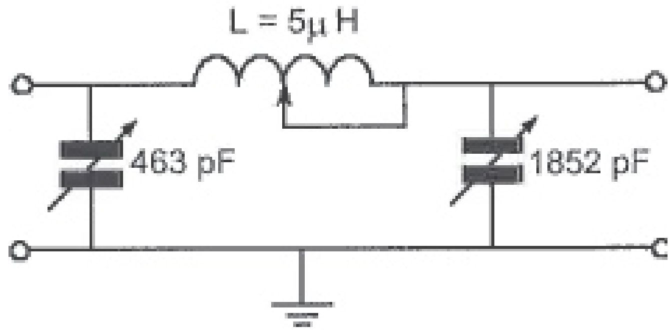
- Frequency range: start f1 Hz, end f2 Hz, n frequency points in log axis

Output:

Calculate impedance Z vs f and write the following.

f(Hz), log10[f(Hz)], Z, abs(Z)

- Example 2



$f = 3.7$ MHz, $Y_0 = 1/50$, Z0 = 50Ω, C1=463pF, C2=1852pF, L3=5μH

1) Calculate S11, S12, S21, and S22 in polar form. Magnitude in natural unit (not dB unit).

2) From calculated S11, S12, S21, and S22, find C1, C2, and L3.

- ## Example 3

f : frequency between 1GHz and 5GHz

1) Calculate S-parameters (S11,S22,S12).

2) From S-parameters, find Z3(=1/Y3), Y1, and Y2.

3) From Z3, Y1, and Y2, find C1, L, R, and C2.

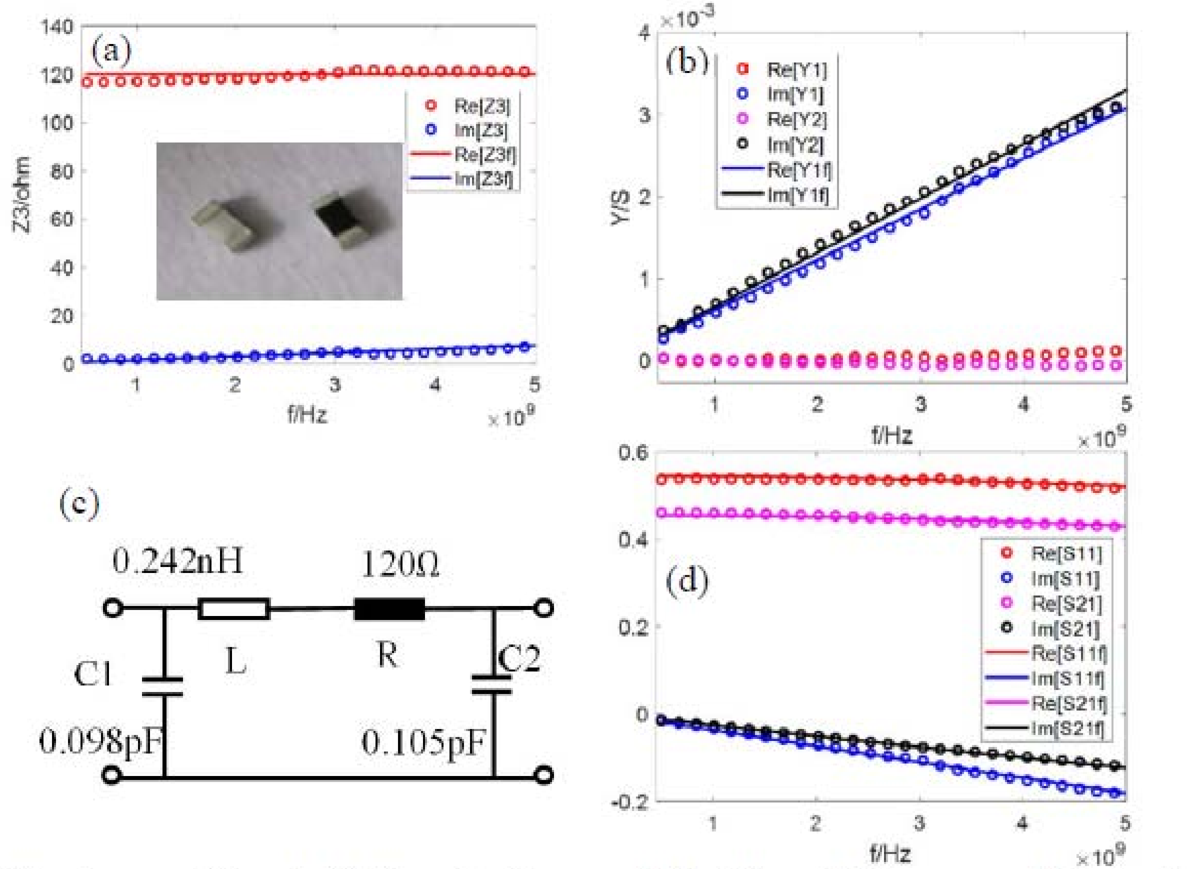


Fig. 3. (a) and (b) The admittance of Y1, Y2 and Y3 in general PI circuit model of SMD resister and their fitting curves. The impedance Z3 is 1/Y3. (c)The finalized circuit model of the SMD resistor. (d) The S-parameters comparison between the circuit model (S_{11}, S_{21}) and the experiment (S_{11f}, S_{21f}).

Fin

(End)