SpecElectronSystems

JSC "NPC SES"

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TECHNOLOGICAL CAPABILITIES

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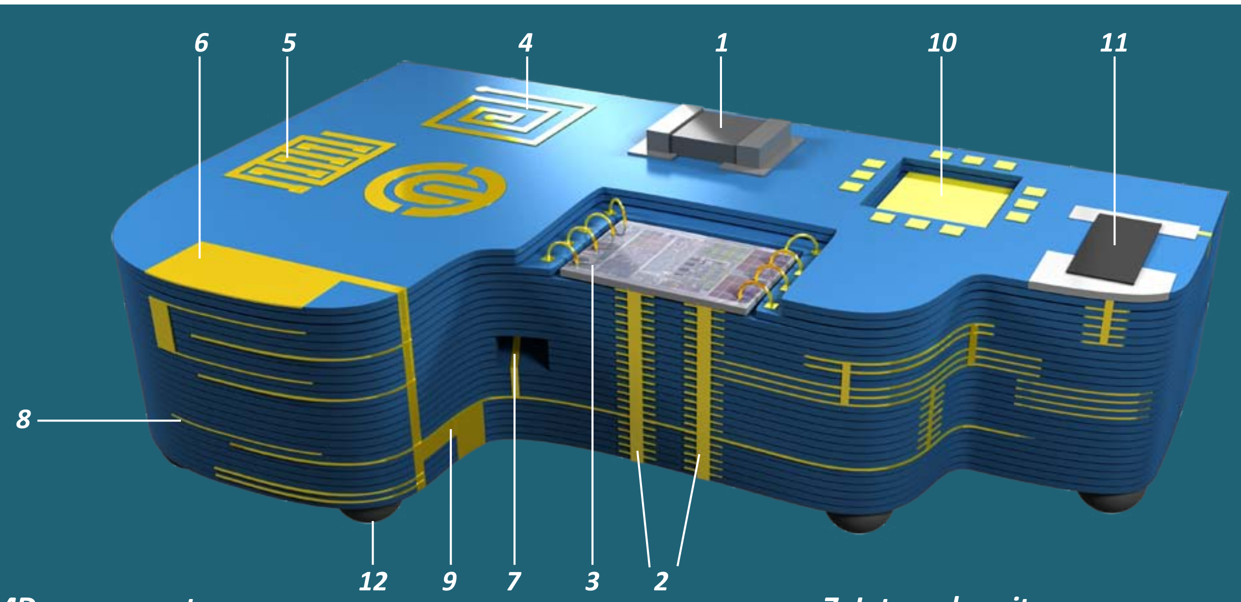
Micromodules on LTCC

Considering the factors, determining the weight, dimensions and mean time to failure of electronic products in such fields of electronics as SHF devices, software-defined radio systems, microelectromechanical systems (MEMS), optical sensors and optical converters, it is impossible to obtain acceptable parameters, especially for severe operating conditions, without 3D-integration. Along with production of traditional 2 dimensional structures on ceramics and polymer materials basis, RPC SES is equipped with technologies of integrated 3D substrate based on low temperature co-fired ceramics (LTCC). RPC SES possesses a complete process cycle of micromodules manufacturing on multilayer (up to 60 layers) ceramics with limit dimensions 160×160 and thickness up to 12 mm.

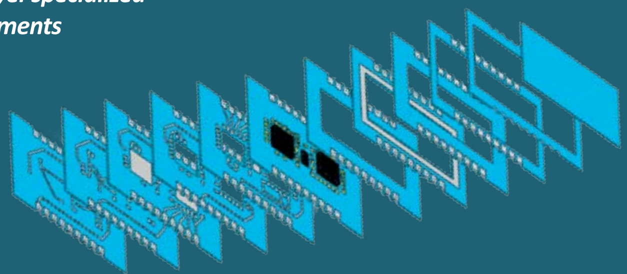
3D integration on LTCC basis



1. SMD-component
2. Termal vias
3. Silicon chip
4. Spiral inductor
5. Planar capacitor
6. Multilayer capacitor
7. Internal cavity
8. Internal conductor
9. Print on the edge
10. Cavity for chip
11. Surface (printed) resistor
12. External contact

Model of multilayer patch antenna

The picture on the left shows a model of internal structure of multilayer specialized 3-D packages for the arrangement of 3 functional packageless elements



The advantages of 3-D micromodules are the following:

- ***Reduction of mass-dimensional characteristics of a product,***
- ***It is not necessary to conform packageless components with substrate,***
- ***Overcoming structural restrictions on voltage isolation parameter, related with breakdown on the metallic cover of packages.***
- ***Reduction of spurious couplings due to 3-D execution of micro-assembly in common package,***
- ***Optimization of wire connections length due to chips assembling inside the well.***

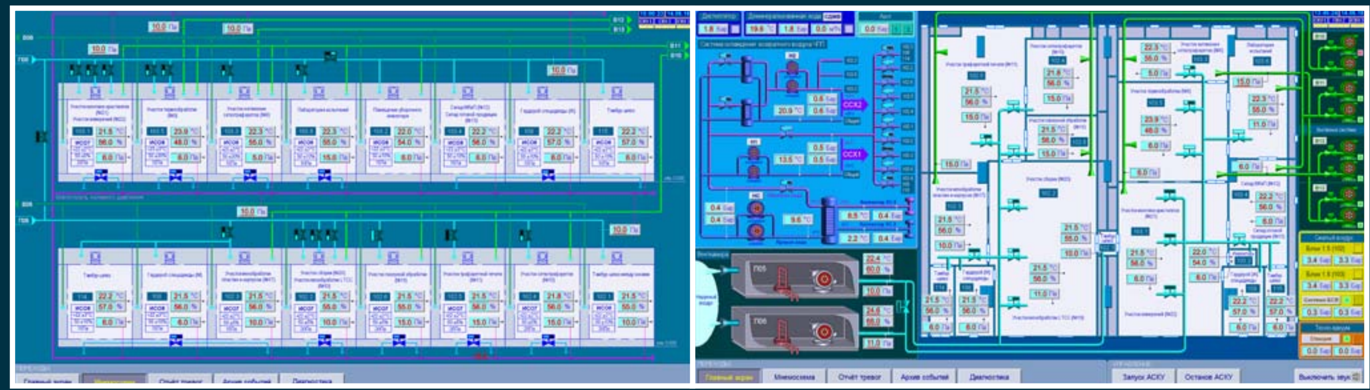
Research and Production Center on Special Electronic Systems (RPC SES)

Being a cluster of microelectronics RPC SES production is located on the territory of special economic zone “Technopolis Moscow”. Process sites occupy over 1000 m² of cleanroom facilities, 700 m² of which possess 7 grade cleanness.

Besides air cleanness, an important factor of microelectronic product quality assurance is maintenance of such micro climate parameters as temperature and humidity, as well as a gradient of their changes. To control dampers and fans, nitrogen and noble gases supply into process installations, as well as coolant and water, there is its own specialized automated control system with visualization and documenting of Supervisory Control and Data Acquisition (SCADA).

For ceramic work pieces annealing and normalization it is necessary to provide specified temperature profiles for prolonged periods of time (over 50 hours). RPC SES’s system of power supply is equipped with 0.9 MW UPS, which is able to exclude unexpected and unwanted events.

RPC SES has video surveillance and video recording system. All movements within RPC SES territory and at individual production sites are monitored by means of automated access system. Quality control system provides monitoring and documenting of each technological operation.

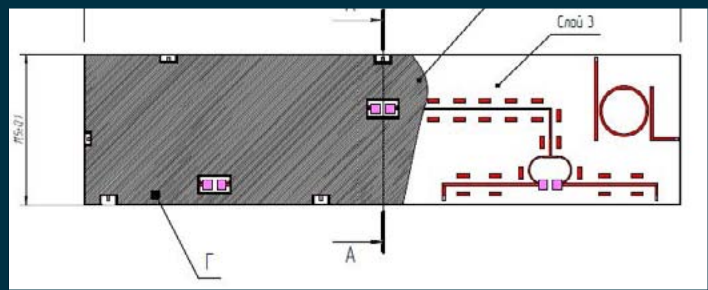


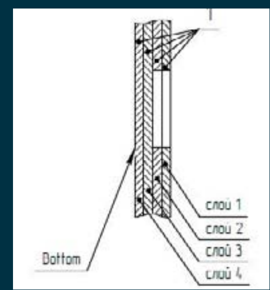
Design and technological training

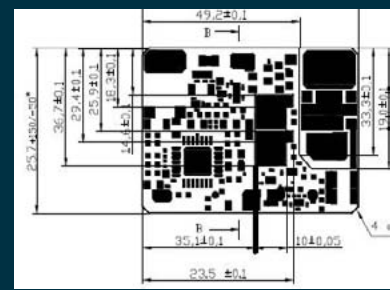
A team of qualified engineers, possessing all necessary knowledges and experience to operate modern equipment, is a pride of RPC SES.

The Engineering Center takes over initial design documentation in any CAD formats and together with customer performs detalization of requirements to future products.

It is also possible to jointly produce the prototypes and trial lots for preliminary functional tests of novel technologies.







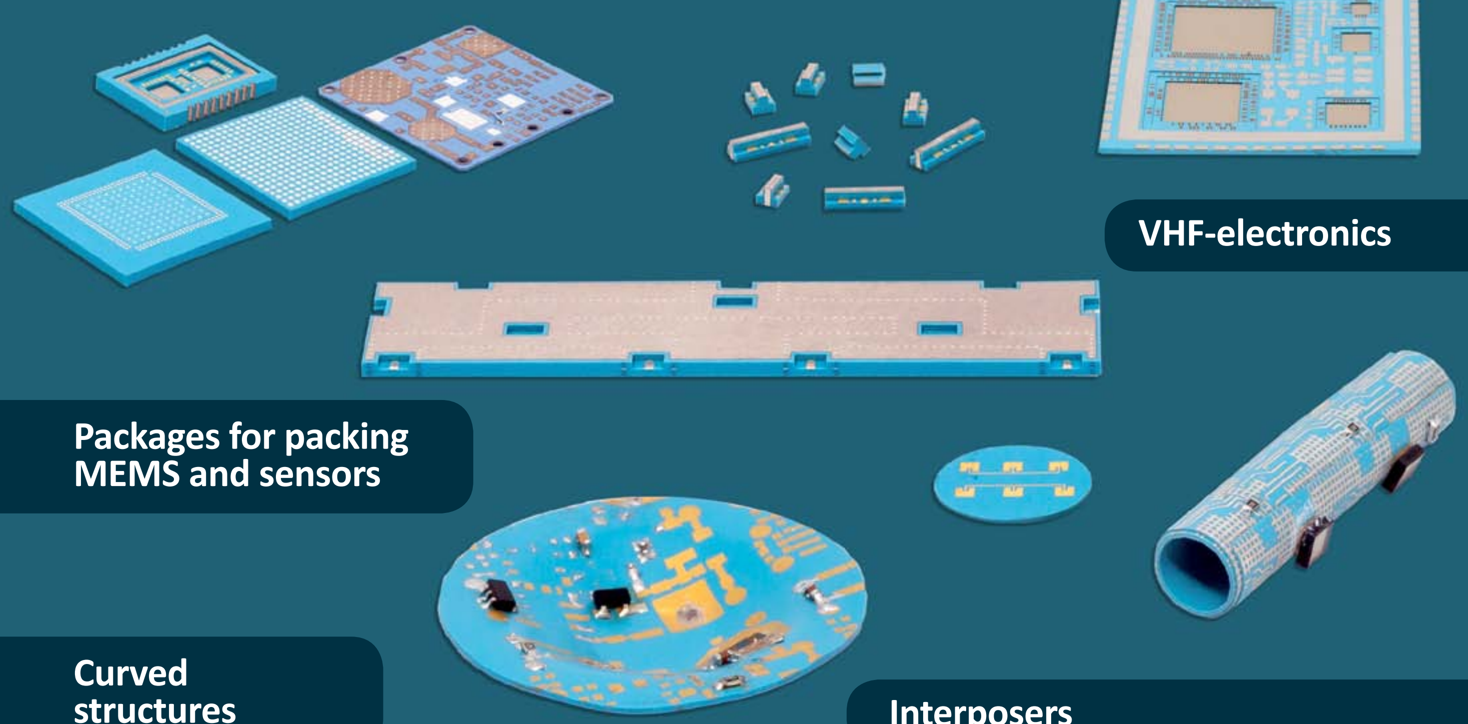
Advantages of thick-film technology on LTCC ceramics

3D-integration	*Transfer of passive elements — capacitors, inductances, microwave lines, resistors – into internal layers of substrate; high values of dielectric constant ε 6.5÷7.8 decrease linear sizes by times and make it possible to implement 3D design of HF modules.*
HF-application	*Operation frequencies – up to 120 GHz, high value of tg δ 0.001÷0.003; LTCC material is a monolith, which preserves its properties in the whole volume, good repeatability at series production of HF , and the process of microwave elements modeling is less complicated considering multiple interfaces of different mediums; it is possible to implement transceiving devices with complex controllable antennas in a single module.*
Suitable for application in severe conditions	*LTCC is able to function durably at operation temperatures up to 350 ˚C; temperature coefficient (TC) varies in the range $3.3\div3.9\times10^{-6}$ ˚C^{-1} and is close to LTTC of silicon; increased stability towards vibrations and single impacts; Young's modulus is in the range 120÷145 GPa; bending strength – in 230÷320 MPa range; Poisson's ratio – in 0.24÷0.25 range; water absorption is actually absent; both dielectric and UHF parameters are durably preserved.*
Structural advantages	*Possibility of developing conductors with low specific resistance by means of Ag-, Au-paste instead of W, Mo. Semiconductive chips are directly installed on substrate; thermal conduction of LTCC equals 3.3÷4.6 W/m-K which is by the order higher than in case of polymers; it is possible to increase thermal conduction of the device by arranging local heat sinks. Breakdown voltage of LTCC is >40 kV/mm; possibility of creating internal voids, including fully metallized and closed, permits one to implement semiconductive and MEMS sensors and converters, channels for liquid cooling. It is possible to seal active sites by radioparent and translucent materials such as silica glass, monocrystals of semiconductors, by LTCC material itself, enabling one to implement VHF (HF), optical and IR detectors.*
Cost-effectiveness	*If compared with ordinary Al2O3-ceramics, the number of firing cycles decrease by 2-3 times at temperature less than 850˚ C; there is no activation of conducting W-, Mo-base and building-up Au- or Ni-layers; small (≤35 µm) substrate buckling, pastes application permits sealing LTCC modules in case of traditional methods, as well as without application of covar frames and caps, possibility of automated in-process control makes it possible to obtain 80% and over yield.*
Ecological compatibility	*If compared with conventional printed circuits on organic dielectrics, LTCC has no wet chemical processes and harmful emissions.*

Solutions implemented at LTCC ceramics

Power electronics

Multichip microassemblies



VHF-electronics

Packages for packing MEMS and sensors

Curved structures

Interposers

Scope of products on LTCC ceramics

Manufacturing stencil screens

Mesh tension

Stencil screens are made on meshes from high quality stainless steel and on cheap polyether sieves as well. Tension force 32–35 N is set by tension sensor with adaptive feedback. Uniform tension is reached, excluding deformations over the whole operation area 1000×1000 mm. Stencils have maximum size of operation field 8˝× 8˝, resolution by topology 100×100 µm with permissible deviation ±5 µm. Tension setting is performed by definite programs with further logging of all performed operations. Correctly performed stencil is a base of process parameters high degree of repeatability .

Stencils for multilayer LTCC modules should provide integral accuracy of coincidence in vertical lines projection and contact pads at 60 layers of ceramic cards, pressed one upon another. Initial data for stencils ordering are Gerber-files, derived from projects, created using any CAD package. Our engineers can perform correct derivation of Gerber-files from CAD programs.

Maximum operation area	*1000×1000 mm*
Maximum operation field	*205×205 мм*
Tension control with feedback	*yes*
Maximum tension strength	*35 N*
Types of mesh	*stainless steel, polyether*
Uniformity of tension	*±5% of upper limit of the force*
Maximum size of stencil screen frames	*650×850 mm*
Maximum stencil field	*205×205 mm*
Resolution by topology conductor/gap	*100×100 µm*
Topology accuracy	*±5 µm*

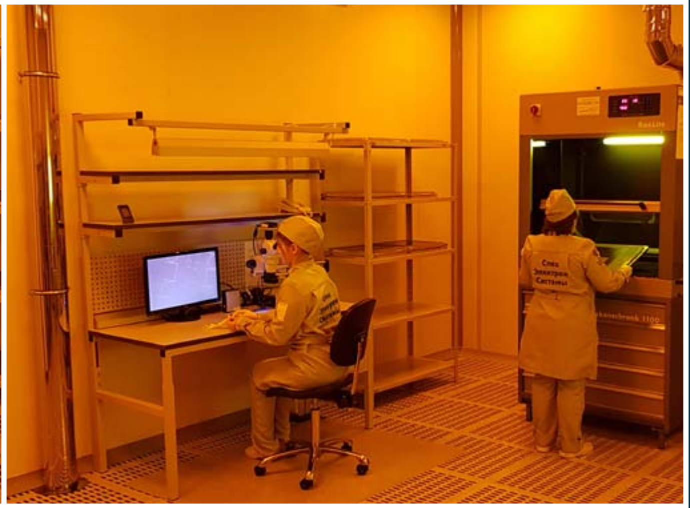
Manufacturing stencil screens

Exposure and drying

On the basis of problems being resolved it is possible to use both liquid and dry film photoresist. At exposing it is necessary to consider luminous flux, actually directed at photosensitive layer. High accuracy of exposure is obtained independently of the state and degree of wear of the installed source of ultraviolet light.

Optically pure glass of copying frame provides 100 percent transmission of UV light, and vacuum antistatic rubber of copying frame together with vacuum gauge at control panel enable one to control photomask clamping. It is possible to use warm and cold regimes of stencil frames drying. After drying finished stencils are inspected at optical installation. Each stencil parameters are measured and recorded.

Maximum size of stencil screen frames	*650×850 mm*
Power of exposure lamp	*4.0 kW*
Distance of exposure	*1,2 m*
Control of exposure time	*up to 600 s*
Light integrator	*yes*
Maximum heating power	*1.2 kW*
Forced ventilation	*yes*
Fan filter	*yes*
Switch key cold/warm	*yes*
Volume of drying cabinet	*5 stencil frames*



Manufacturing 3D ceramic modules

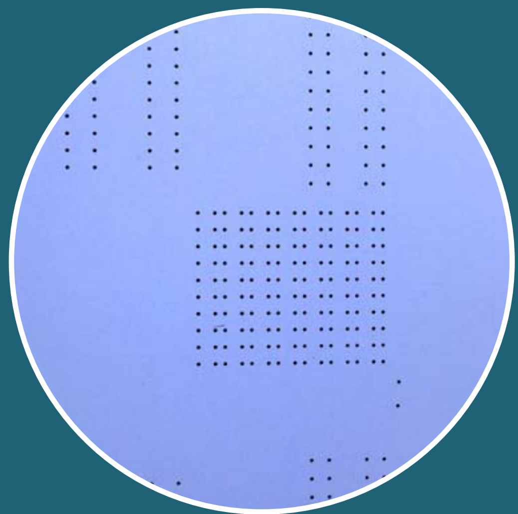
Punching holes in ceramic cards

Eight puncheons with different nominal sizes are simultaneously installed at punching press for punching ceramic plates with 5˝, 6˝ and 8˝ sizes. Average punching rate constitutes 3–6 holes per second. Using respective puncheons combinations it is possible to punch out lines of any complexity. Optical inspection system performs automatic sorting into trays “suitable –unsuitable”. Loading-unloading of material is carried out in automatic regime.

Maximum punching rate	*for Ø 1 mm holes – 8–10 holes/s with 1 mm increment*
Maximum punching area	*200×200 mm*
Maximum plate thickness	*500 µm*
Round puncheons	*Ø 110, 150, 200, 250, 300, 500, 1000 µm*
Square puncheons	*1, 2, 5 mm*
Control of tool condition	*automated*
Positioning accuracy	*±5 µm*

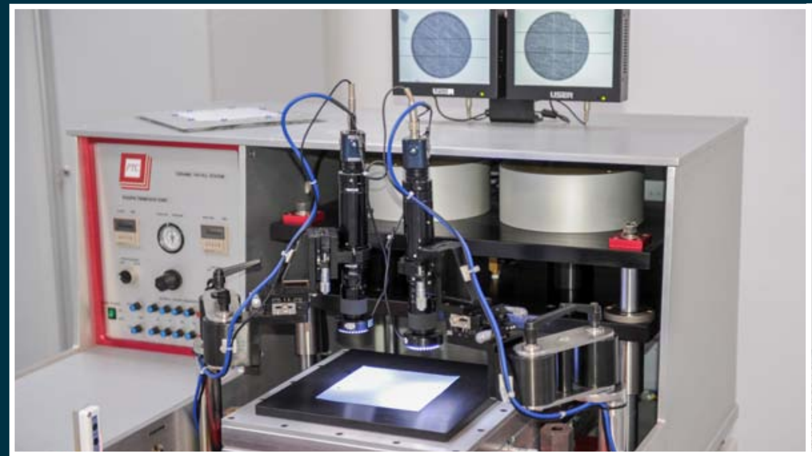
Different systems of cards loading are available:

- *Manual loading/unloading of plates*
- *Automated loading/unloading from cassette into cassette*
- *Ceramic plates are cut out from rolls automatically and after punching are unloaded into cassette*



Manufacturing 3D ceramic modules

Filling deep holes with conducting pastes



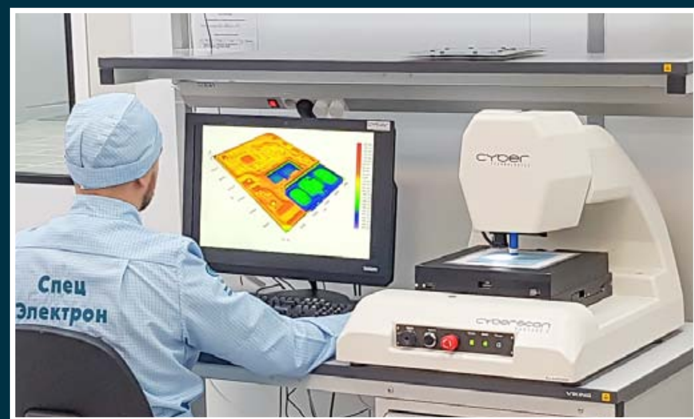
It is possible to fill holes in case of h/Ø >> 2

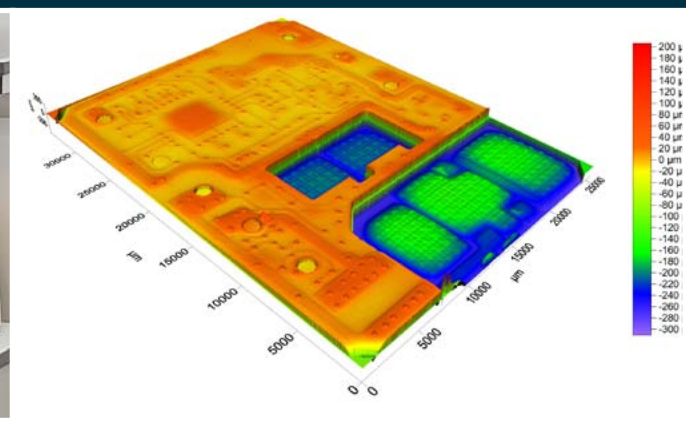
Conducting pastes viscosity control

Operative control of deposited topology

Printed plates are subjected to operative control of conductive layer parameters. The process of control may be carried out manually or in semiautomated regime. 3-D colored images of space structures are created. Images and digital values of measured parameters are recorded.

Maximum size of measured surface	*305×850 mm*
Maximum weight of measured substrate	*6.8 kg*
Maximum automatic head displacement along X and Y axes	*200×200 mm*
Resolution by X and Y axes	*1 µm*
Maximum head displacement along Z axis	*40 mm*
Resolution by Z axis	*0.2 µm*





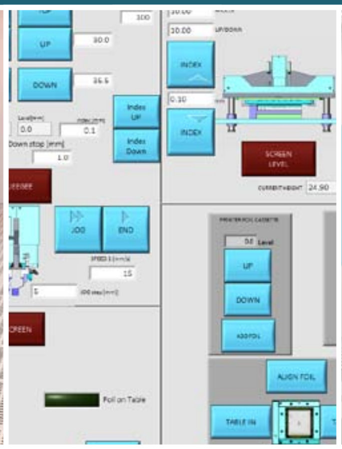
Manufacturing 3D ceramic modules

Screen printing

Deposition of conducting tracks and passive elements is carried out using screen printing with materials of nominal sizes 5”, 6” and 8” manually and in automatic regimes. Squeegee blade displacement is managed by specified program. For exact plates positioning by optical marks the machine vision function is used.

Quick stencils replacement and setting is organized. The table is operated by a joystick, all printing parameters are set down by touch screen. It is possible to deposit topologies at side internal and external surfaces of work pieces, and to metallize holes on vertical surfaces with diameter > 0.5 mm.

Maximum printing area	*210×200 mm*
Squeegee blade velocity	*0–350 mm/s*
Squeegee blade effort	*0–250 N*
Accuracy	*±5 μm*
Nominal stencil size	*450×450x25 mm*
Maximum stencil size	*550×550×25 mm*
Via holes filling	*yes*
Frame for stencil tensioning and frame fixation	*yes*
Substrate fixation	*by vacuum*
Drying	*yes*
Antistatic substrate cleaning	*yes*
Automatic paste feeding	*yes*

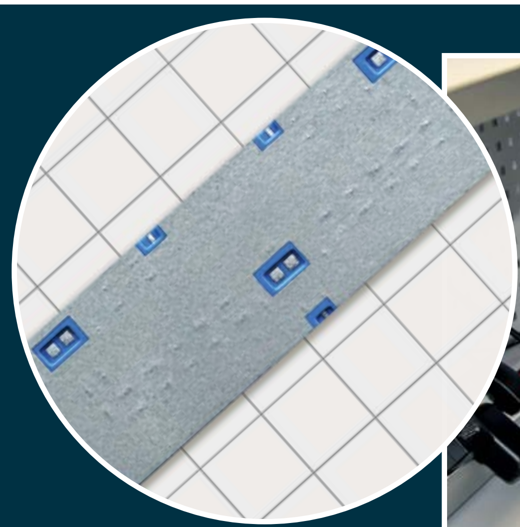

Manufacturing 3D ceramic modules

In process control

In process control is carried out at all technological stages, providing topology creation. Controllers workstations are equipped with certified stereoscopic measuring microscopes.

Amplification, times	*within ×4 ÷ ×100*
Linear field of view	*within 39÷2.4 mm*
Operation distance, at least	*95 mm*
Light source, halogen lamp	*20 W*


3D image, giving a clear idea of vertical size




- *Magnification from 2 to 200 times*
- *Big operation distance at big field of view*
- *Integrated color digital HD-camera*

Manufacturing 3D ceramic modules

Manufacturing 3D ceramic modules

Packages assembly

Non-fired ceramic plates (cards) with nominal sizes 5”, 6”, 8” are assembled into packages containing 60 layers with registration accuracy ±5 µm.

Functions of mylar substrate separation from ceramics while ceramic plate loading with topology up or down have been implemented. It is possible to assemble packages from single plates or from in advance prepared subpackages without loss of accuracy. In some cases assembled package can be laminated (converted into monolith) using hydro-press, integrated into assembling installation, excluding thus the operation of isostatic lamination.


Isostatic lamination

Uniform pressure is provided over the whole surface of ceramic stack. Materials of neighbouring plates diffuse from one plate to another and the assembled package obtains isotropic structure. Isostatic lamination is carried out in reservoirs with deionized water under applied pressure. “Crude” ceramic work pieces are sealed in plastic packages and then installed into cassette. Ceramic work pieces are pressed according to the program specified by operator.

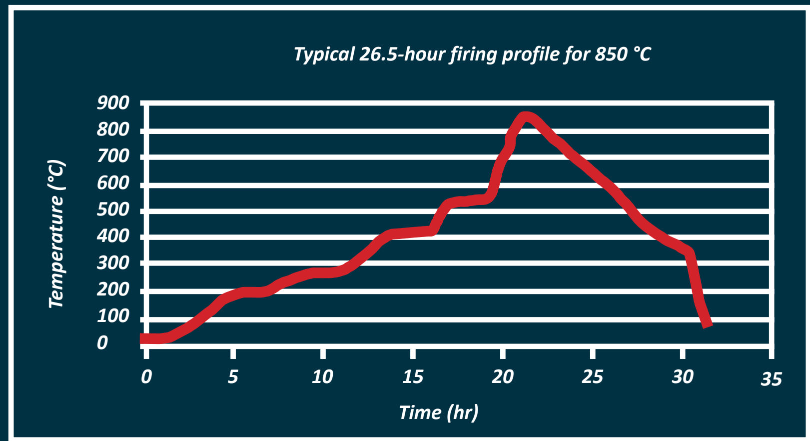
Separation of ceramic work pieces

Non-fired ceramic package is separated into orthogonal work pieces with dimensions starting from 1×1 and thickness up to 12 mm.
For exact positioning by optical marks the machine vision function is used. Dimensions of ceramic work pieces are up to 254×254 mm; stainless steel or carbid blades; temperature of worktable is max. 80 ˚C; cutting blade temperature – max. 150 ˚C; step accuracy – 0.01 mm.

Thermal treatment

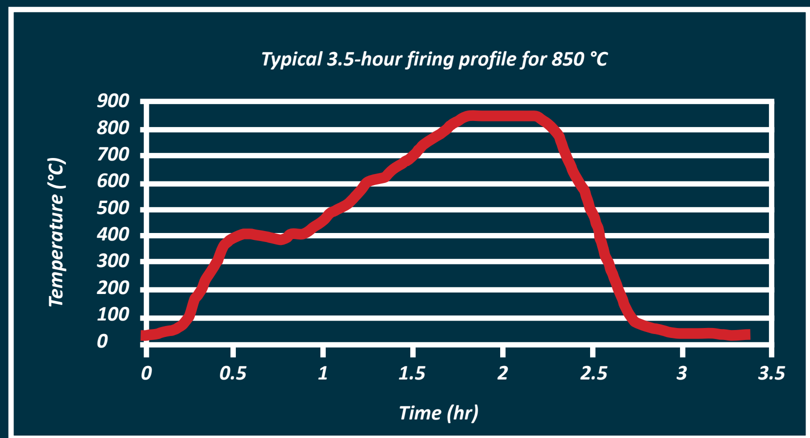
Firing (sintering) of laminated ceramic work pieces is carried out in conveyor furnace in atmospheric environment at typical temperatures 850–900 ˚C and firing cycle from 30 to 1600 min. Besides firing, vacuum soldering at temperatures up to 1000 ˚C in vapors of formic acid, in nitrogen, in forming gas, in argon or in helium is carried out at the site. Soldering installation includes function of semiautomatic cleaning after soldering using flux for transfer to soldering without flux. It is possible to perform selective soldering of discrete SMD-components on the furnace with programmable temperature profile in atmospheric air and in nitrogen as well, thus enabling one to provide higher quality of soldered joints.

For assembling highly reliable components flux-free soldering is used with precision control of temperature in inert gases atmosphere with vacuumetric pressure lower than 50 mTorr and up to pressure 4.5 bar.



Reference points of T-profile 26.5 hr

Site	Temperature (°C)	Time (min)	Rate of temperature rise (°C/min)
1	25–195	260	0,7
2	Exposure 195–210	95	–
3	210–265	80	0.7
4	Exposure 265–275	110	–
5	275–415	150	0.9
6	Exposure 415–420	115	–
9	420–530	58	1.9
10	Exposure 530–535	105	–
11	535–850	125	2.5
12	Exposure 850	20	–
13	850–300	420	–1.3



Reference points of T-profile 3.5 hr

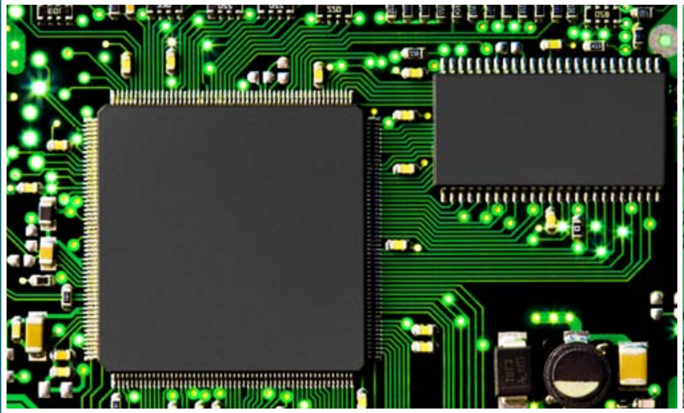
Site	Temperature (°C)	Time (min)	Rate of temperature rise (°C/min)
1	25–400	–	13.5
2	Exposure 400	45–60	–
3	400–600	–	4.5
4	600–850	–	7.2
5	Exposure 850	20	–
6	850–50	–	–20.4

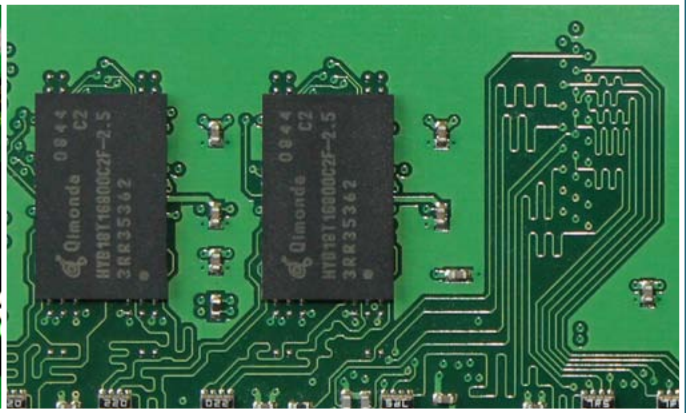
Assembling operations

Assembling SMD-components

SMD-components are assembled by means of semiautomatic installer under optical magnification by profiling 3-channel soldering stations. Installer also performs recording function.

Maximum size of installed board	*297×420 mm*
Minimal size of SMD-components	*0201*
Minimal size of dipper drop	*0.2 microliter*
Number of cells in rotating cassette	*160*
Number of band feeders	*6*
Determination of installation coordinates	*manually by TV-optics*
Grip and orientation of component	*semiautomatically*





Assembling operations

Functional electrical control

Assembled micromodules are then tested at flexible programmable system for electrical measurements by resistive and capacitance methods. Tests are carried out in automatic regime from both board sides. Probes of measuring devices provide soft contact with pads without damaging. Control program permits testing components at internal layers and on planes shifted relative to base plane by ±1.5 mm. Testing results are recorded.

Number of independent flying probes	*8 (4 on each side)*
Speed of automatic measurements	*9000 per minute*
Maximum size of tested board	*540×610 mm*
Minimal diameter of contact pad	*50 µm*
Conductors testing by resistive methods	*1–10 кOhm*
Testing by capacitive methods	*0.1 pF – 100 µF*
Testing of isolation by resistive methods	*10 кOhm – 100 GOhm*
Low voltage test of isolation	*1–100 V*
High voltage test of isolation by resistive methods	*100–500 V*

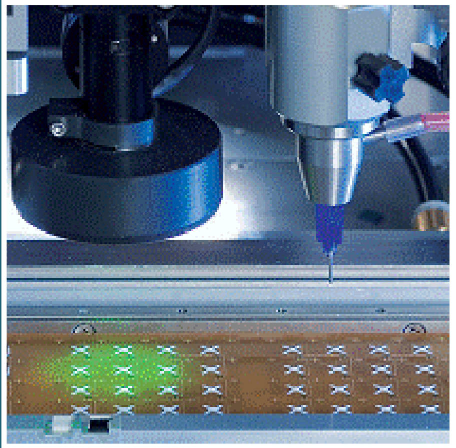
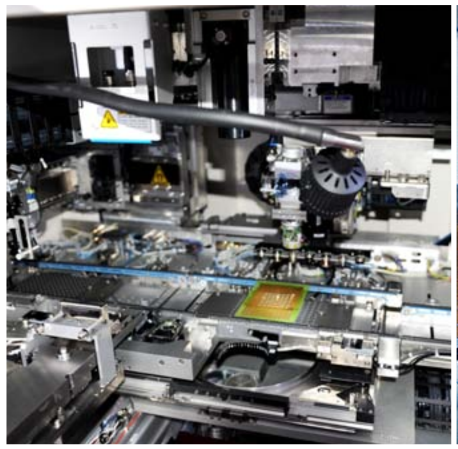
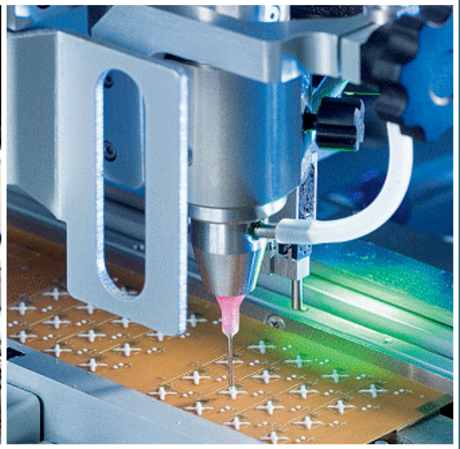
Assembling operations

Semiconductor chip assembly

Chips are assembled using resistance reactive soldering and thermal compression, including preforms made of eutectic alloy. Die attachment is performed on polymer adhesive pastes. It is possible to vary the heating of worktable and tool. Machine vision identifies the borders of topology contours and matrix codes. Tool changing is performed automatically. Chips with leads are installed by flip-chip method. There are three types of dispensers: air-vacuum, auger type and spray type. Chips are extracted from film carrier by manipulator using five types of digs without shifting neighboring elements.

Operation area of substrate	*330×203 mm*
Sizes of assembled dies	*0.17÷50 mm*
Thickness of assembled dies	*0.02÷7.0 mm*
Controlled hold-down pressure	*up to 70 N*
Assembling accuracy	*±10/3σ*
Number of automatic holders	*7*
Types of carriers	*FR4, ceramics, BGA, DIP lead frames, Waffle Pack, GEL PACK, JEDEC trays*



Assembling operations

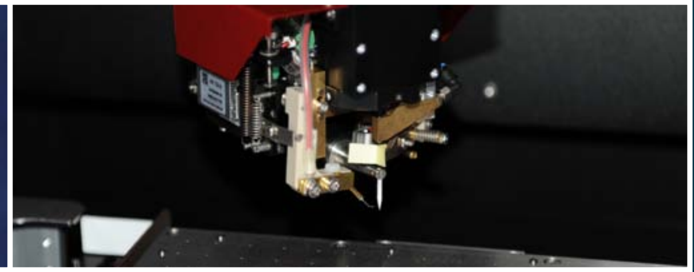
Electrical attachment of semiconductive dies

Contact pads on semiconductor are joined with substrate contacts by means of metallic wire made of Au, Cu or Al. Bonding of Au-wire is performed by “ball-wedge” method. Bonding of Al- and Cu-wire is performed by “wedge-wedge” method. It is possible to join dies located in ”deep well”. Bulk testing of attachments on fatigue endurance (breaking off and shear) is performed with maximum load up to 100 N and 200 N, respectively. Installation is equipped with video and recording system for all die attachment and testing stages.

Material of round contact wire	*Au, Cu, Al*
Diameter of wire	*17–100 µm*
Material of flat ribbon fingers	*Au, Cu, Al*
Sizes of flat ribbon fingers	*250×50 µm*
Precision of positioning	*1–3 µm/3σ*
Programmable hold-down for wires	*0.5÷20 N*
Programmable hold-down for ribbons	*up to 40 N*

Quality of leads bonding is inspected by automatic device with machine vision and with program for detailed reports generation.

Types of examinations, accuracy of measurements	
on breaking off	*up to 1000 N*
on shear	*up to 5000 N*
on pressing	*up to 500 N*
Motorized worktable	*160×160 mm*
resultant precision by loads	*±0.1%*
Precision of shifting at displacement along Z axis by 2 mm	*± 0.25 µm*

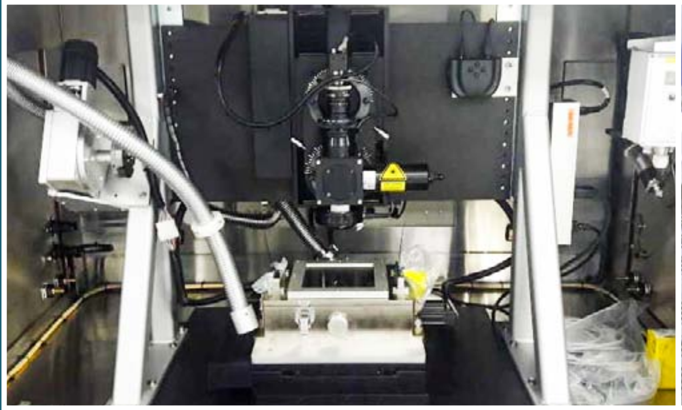
Assembling operations

Sealing

Vacuum tight sealing, assembling micromodules of metal lids on ceramic substrate, lids from quartz glass, semiconductive plates are carried out by seam and laser welding with sealing examination.

Sealing is performed in glove box in nitrogen atmosphere, in forming gas or in vacuum. In preparing components for sealing, vacuum furnace with gateway is used. It is possible to create packages with ordinary metallic leads and vacuum-tight and wide-band VHF-leads with specified impedance and small losses. Before welding, preliminary fixation with computer control of accuracy and high resolution video surveillance is carried out.

Size of gateways	*305×195×195 mm*
Size of component (machine vision and preliminary fixation)	*3÷110 mm*
Size of component without machine vision and preliminary fixation	*3÷203 mm*
Precision of lid arrangement	*±0.08 mm*
Welding force is programmable	*5÷30 N*
Linear welding force	*0,25÷38 mm/s*

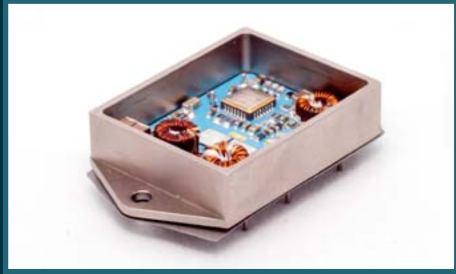


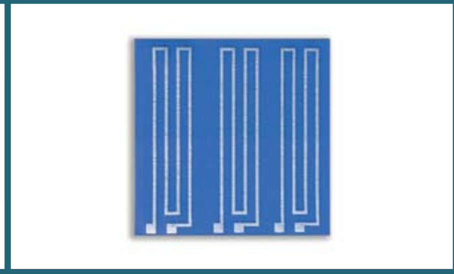
Assembling operations

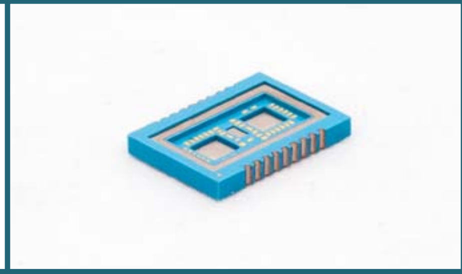
Acceptance of finished products

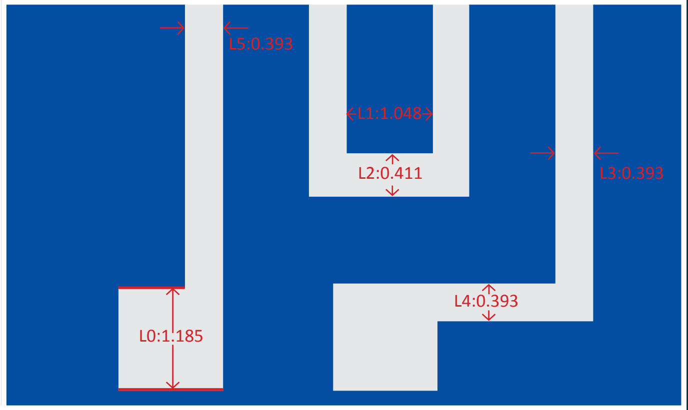
Licensed controlling and measuring 3D complex for acceptance of finished products is equipped with motorized worktable and motorized drive along Z axis.

Installed software enables one to perform measurements of linear sizes of finished products with further recording of acceptance results.









Range of measurements	
X	*150 mm*
Y	*150 mm*
(rough displacement) Z	*230 mm*
(fine displacement) Z	*230 mm*
Maximal load of glass plate	*15 kg*
Sensor resolution	
X	*0.001 mm*
Y	*0.001 mm*
Z	*0.0005 mm*
Measurements repeatability	
X	*0.002 mm*
Y	*0.002 mm*
Z	*0.008 mm*
Measurement error	$U_{95}2D = 4+(5,5L/1000)\ \mu m$

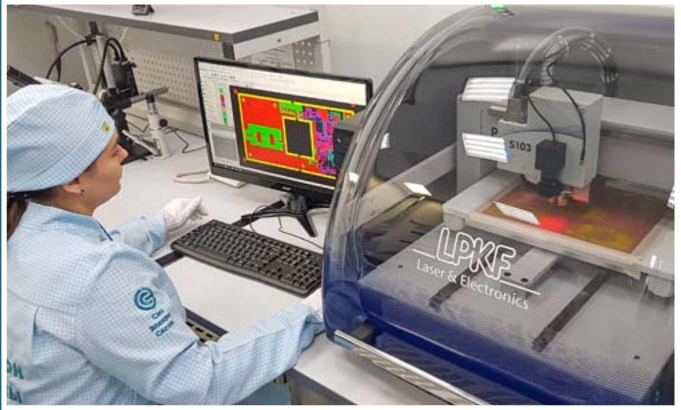
Prototyping on VHF-materials

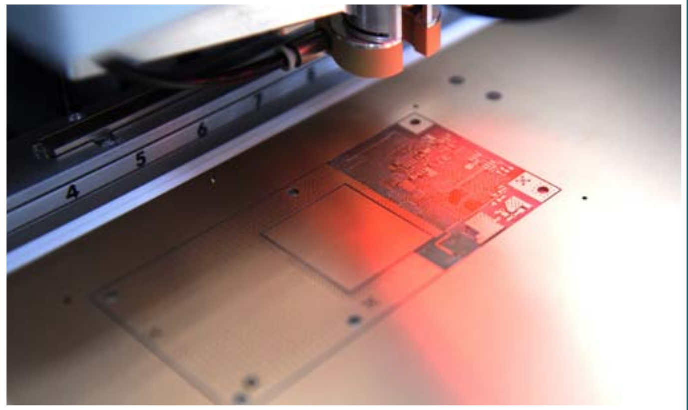
Mechanical prototyping

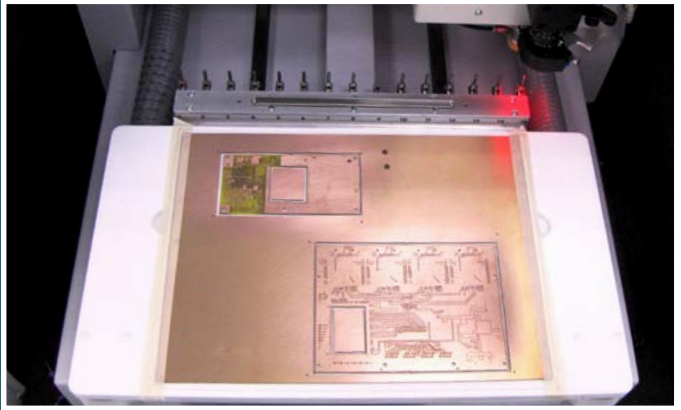
You can place orders for RPC on VHF-laminates and glass-fibre plastic. Resolution by topology conductor/gap is 100/100 µm for digital devices and 150/150 µm — for VHF-laminates.

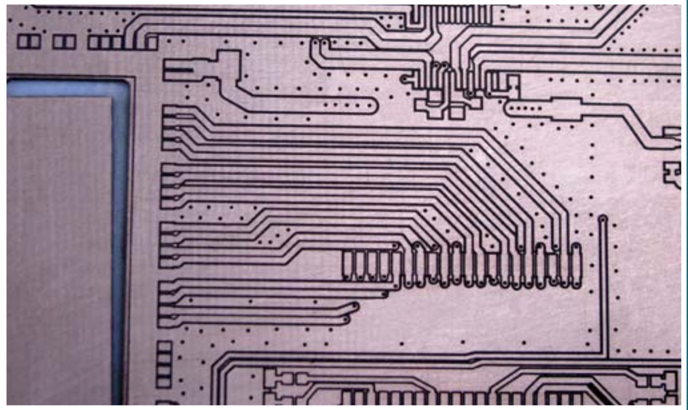
We offer layout of non-fired ceramic work pieces and plates from polymer materials of any form.

Operation field	*229×305 mm*
Maximum workpiece thickness	*2.5 mm*
Min. hole diameter	*100 µm*
Resolution of milling	*0.5 µm*
Repeat accuracy	*±1.0 µm*
Max. velocity of spindle rotation	*10^5 rev/min^{-1}*
Production rate	*100 holes/min*
Volume of automatic device of tool changing	*15*





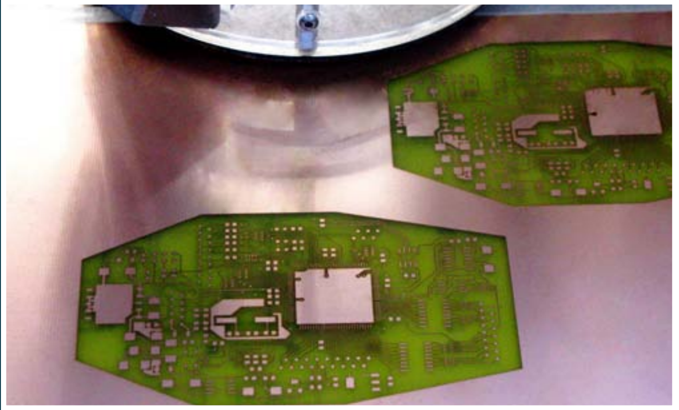


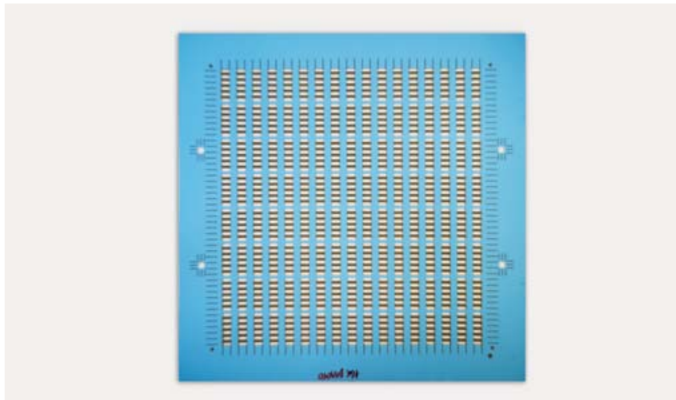


Laser prototyping

We process plates with sizes up to 229×305 mm from foiled laminates, fired alumina ceramics, silica glass, semiconductive monocrystals of Si, Ge, GaAs and others. UF laser with beam diameter 15 µm provides high purity of slice surfaces. On substates from aluminum nitride or substrates covered by deposited conductive layer it is possible to create topology with resolution line/dielectric 50/20 µm. The device is equipped with special video system for visualization of micromaterials processing. Specialized laser is adapted for marking in accordance with GOST 30668–2000 “Marking products of electronic engineering”.

Operation field	*229×305×10 mm*
Laser wave length	*355 nm*
Controllable modulation frequency of beam	*25÷300 kHz*
Rate of topology deposition on 18 µm Cu-foil	*200 mm/s*
Cutting rate of glass-fibre plastic with thickness 0.5 mm	*200 mm/s*
Min. diameter of focused laser spot	*20 µm*
Resolution conductor/gap on 18 µm Cu-foil	*50/20 µm*
Accuracy of processing	*± 1.98 µm*





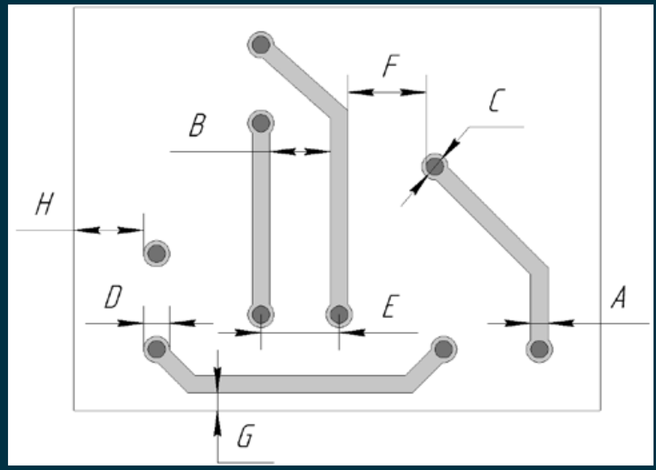
Systems of ceramics and pastes used for metallization

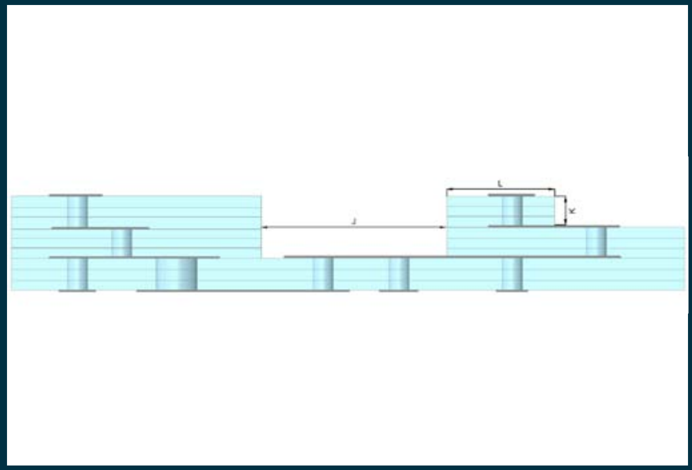
Name	KEKO	Dupont		FERRO	
	SK47	951 (for frequencies up to 10 GHz)	9K7 (for frequencies up to 100 GHz)	L8 (for frequencies up to 10 GHz)	A6M-E (for frequencies up to 10 GHz)
Thickness of "crude" layer	0.050 mm	0.051 mm	–	0.0625 mm	–
	0.115 mm	0.114 mm	0.127 mm	–	0.127mm
	0.165 mm	0.165 mm	–	–	–
	0.254 mm	0.254 mm	0.254 mm	0.250 mm	0.254 mm
Shrinkage factor along X andY axes	13±0.5%	12.7±0.3%	9.1±0.3%	13±0.3 %	15.4±0.3 %
Shrinkage factor along axis Z	17±0.5%	15±0.5%	11.8±0.5%	17±0.3 %	24.0±0.3 %
Bending strength, MPa	> 200	320	230	>275	170
Density of fired ceramics, g/cm³	> 2.9	3.1	3.2	3.1	> 2.45
Surface roughness, µm	0.6	<0.35	0.52	–	–
Ability of voids creation	yes	yes	yes	yes	yes
Dielectric permeability	7.1±0.2 (at 10 GHz)	7.8 (at 10 GHz)	7.1 (at 10 GHz)	7.3±0.2 (at 10 GHz)	5.9 (at 10 GHz)
Dielectric dissipation factor	0.003 (at 10 GHz)	0.014 (at 10 GHz)	0.001 (at 10 GHz)	< 0.002 (at 10 GHz)	< 0.002 (at 10 GHz)
Resistance of insulation	> 1012 (100V DC)	> 1012 Ω (100V DC)	> 1012 Ω (100V DC)	> 1012	> 1012
Breakdown voltage, V/25 µm	>1000	> 1000	> 1100	> 1250	> 5000
Thermal expansion, ppm/ °C	6.9	5.8	4.4	5.8	7
Heat conduction, W/mK	2.9	3.3	4.6	3	2.0
Material of conductor	Ag, Au, AgPd, AuPt	Ag, Au, AgPd, AuPt, AgPd, AuPtPd		Ag, Au, AgPd, AuPt, AuPtPd	
* detailed material characteristics are provided in manufacturer's documentation					

Rules and restrictions in design

Designation of distance	Name	Standard, mm	Special, mm
Line width, min	A	0.125	0.1
Line to line spacing, min	B	0.125	0.1
Via diameter	C	0.11/0.2/0.25/0.3/0.5/3	< 0.1
Via pad diameter	D	C + 0.1	C + 0.05
Via to via spacing, min	E	3C	2C
Via to line spacing, min	F	0.125	0.075
Part edge to conductor spacing	G	> 0.25	< 0.15
Part edge to via pad spacing	H	0.3	0.2
Cavity width, min	J	0.5×0.5	
Cavity depth	K	< 0.8	0.1
Cavity wall thickness	L	≥ K	

*For expanded manual, please contact us at the email address vag_av@npc-ses.ru





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