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Evaluation of Mechanical Strength of Miniaturized Functional Substrates and Components in Different Environments

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Abstract—**Functional components such as multilayer, low-temperature cofired ceramics are examples of the combination of a ceramic-based substrate with internal electrodes as well as surface features (e.g., metallization, contacting pads, and cylindrical vias) employed to provide the component with a given functionality. Another example is that of functionalized silicon chips to be embedded into polymer circuit boards to enhance integration and save costs. The functionality of the system can be influenced by the mechanical reliability of the different components. Due to miniaturization and design complexity, no standard methods for mechanical testing can be applied for the characterization of these brittle components. In this work, an experimental approach is presented that enables the determination of the strength distribution in functional components (e.g., rectangular plates as small as $2 \times 2 \times 0.12$ mm^3) in different environments at different temperatures. The method is based on localized biaxial testing using a ball-on-three-balls fixture. The high accuracy of the test allows quantification of the effect of surface quality, surface features, and/or metallization (e.g., contact pads or cylindrical vias) on the component strength distribution. Experimental findings show that the strength distribution of ceramic components can be affected by environmental degradation, whereby subcritical crack growth phenomena can be enhanced in environments with high relative humidity. In addition, metallization at the surface subjected to tensile stresses can even raise the strength of the component, acting as a protective layer against environmental degradation, whereas cylindrical vias can become weak points in the design. It is shown that functionalized layers such as those used in silicon chips can have a significant effect on the strength parameters, thus influencing the lifetime of the device.**

Keywords—**Miniaturized mechanical testing, silicon, functional components, strength, ball-on-three-balls, subcritical crack growth**

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Introduction

Within the microelectronics field, many applications involve combinations of ceramic and metal constituents. Functional components such as multilayer piezoelectric actuators, multilayer ceramic capacitors, multilayer varistors, low-temperature cofired ceramics (LTCC) or semiconductors, among others, are examples of combination of a ceramic-based (or silicon-based) substrate with internal electrodes as well as surface features (e.g., metallization, contacting pads, cylindrical vias) This combination of materials provides the component (or system) with a given functionality.

Due to the different properties of the materials involved (e.g., thermal expansion coefficients, elastic constants, yield strength), components can be subject to internal stresses during fabrication, which may induce cracks that truncate the electrical performance of the device [1-4]. Other processes after fabrication (e.g., packaging of embedded silicon dice) can also involve high tensile stresses, which may damage the component [5, 6]. In addition, mechanical stresses occurring during service conditions (e.g., rapid temperature changes, bending, contact damage) can also affect the structural integrity of the device.

As a consequence of the brittleness of ceramic- (or silicon-) based materials, the initiation of damage (e.g., onset of cracks) is usually followed by catastrophic failure of the component and/or device, associated with the unstable propagation of the initial crack in the ceramic part [7]. Fig. 1 shows an example of the failure of an LTCC-based printed circuit board (PCB) upon mechanical loading [8]. Fracture was originated in the vicinity of a "through-thickness" connecting via.

Characterizing the mechanical behavior of brittle materials is crucial to derive design rules and lifetime prediction models for functional components and systems. In this article, the mechanical biaxial strength of substrates and functional brittle components are characterized using the ball-on-three-balls (B3B) testing method [9]. Typical loading conditions and environments are selected aiming to reproduce possible loading scenarios during service. The testing methodology is described and applied to (1) silicon dice with and without patterned metallization and (2) LTCC samples (with and without surface vias) in different environments. Strength results are interpreted

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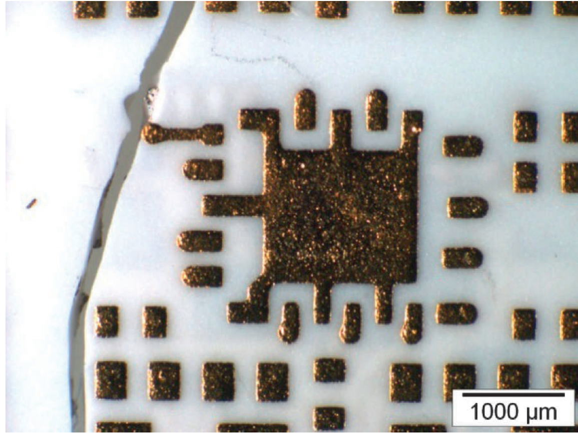

Fig. 1. Fracture of an LTCC component upon mechanical loading. Failure originated near a through-thickness via [8].

in the framework of Weibull statistics. A short overview on the fracture of brittle materials is also provided.

Strength of Brittle Materials and Components

The fracture of brittle materials can be described by the linear elastic fracture mechanics based on the well-known Griffith/Irwin energy balance criterion. Assuming linear elastic material behavior, a crack will propagate under a uniform applied tensile loading normal to the crack plane if a certain combination of the applied stress, σ, and the crack length, a, reaches a critical value. This can be expressed as:

$$\sigma_{\mathrm{f}} \cdot (\pi a)^{1/2} = \frac{1}{Y} \cdot K_{\mathrm{Ic}} \tag{1}$$

where K_{Ic} is the "fracture toughness," i.e., the resistance of a material to the propagation of a crack, and Y is a dimensionless constant that depends on the crack configuration, geometry, and loading situation [10].

The mechanical stress responsible for the failure of the component, σ_{f}, is termed "mechanical strength." Assuming a constant value for K_{Ic} in brittle materials (in absence of R-curve behavior), a consequence of eq. (1) is that the strength is to be related to the size of the critical "flaw," a, responsible for the fracture. Typical flaws in this kind of materials are known to be: (1) pores, (2) agglomerates, (3) second phases, (4) surface features, and (5) microcracks, which may be found at the surface or in the interior of a given part [11]. As a consequence of the different type, size, location, and "severity" of flaws, the mechanical strength in brittle materials or components cannot be defined as a single value, but as a distribution function. Hence, the evaluation of the strength requires testing a set of samples under the same loading and environmental conditions. The resulting distribution of strength values is very much related to the defect size distribution in the material [12, 13]. Hence, the probability of failure under an external applied stress corresponds to the probability of finding a critical defect of a certain size, as can be inferred from eq. (1). For a particular crack-size frequency distribution as encountered in many brittle materials, a so-called "two-parameter" Weibull distribution can be employed to fit the strength data [12, 14], according to the probability function, F, given by:

$$F(\sigma, V) = 1 - \exp\left[-\frac{V}{V_0}\left(\frac{\sigma}{\sigma_0}\right)^m\right] \tag{2}$$

The first parameter, the so-called characteristic strength, σ_0, is the stress at which, for specimens of volume $V = V_0$, the failure probability is: $F(\sigma_0, V_0) \approx 63\%$ [14]. Independent material parameters in eq. (2) are m and $V_0 \cdot \sigma_0{}^m$; the choice of the reference volume V_0 influences the value of the characteristic strength σ_0. The second parameter, m, is the Weibull modulus; it describes the scatter of the strength data. The Weibull modulus is calculated according to Norm EN-843-5 (see [15]) using the maximum likelihood method to fit the failure stress data, as represented in a Weilbull diagram. The 90% confidence intervals for m are also calculated according to EN-843-5.

A direct consequence of Weibull statistics is that the strength of "Weibull materials" depends on the size and frequency of critical defects in the material, which can differ from specimen to specimen, sample to sample, and component to component (see details in [10]).

Furthermore, applied (uniaxial) constant loads over a certain period of time may cause "delayed failure" of a brittle component, thus the probability of failure may differ from that estimated using Weibull statistics. The growth of natural defects (or cracks) upon the action of tensile loads over time is called subcritical crack growth (SCCG) [16]. This SCCG phenomenon has been reported in glass-containing materials (e.g., soda lime glass [17]) and in some structural and functional ceramic materials (e.g., alumina [18] or lead zirconate titanate [19]) subjected to tensile stress, especially in humid environments, where cracks can even grow due to applied stress intensity factors, K_{I}, well below the toughness, K_{Ic}, of the material [20-22].

In addition to these "natural" defects, other sources of failure, especially in components consisting of different material classes, must be considered. For instance, surface features (e.g., contact pads, vias) or materials junctions (e.g., electrode tip inside a ceramic matrix) may exert an additional stress concentration effect upon external applied loading, thus influencing the (apparent) strength of the component. As a consequence, the strength distribution in components may be significantly different from region to region (depending on the surface feature and internal architecture [23]), as well as different to that of the substrate material. As a result, a combined effect of environmental degradation and geometry features can not only decrease the strength but also affect the lifetime and mechanical reliability of brittle functional components.

Testing of Miniaturized Components

In addition to the difficulties of characterizing the strength of a particular material due to its stochastic character, measurement uncertainties during mechanical testing may also play an important role. A random (or a systematic) error in the measurement may mask the "natural" scatter of the strength related to the defect size distribution (see details in [24]). As a

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consequence, different parameters affecting the strength (e.g., environment) might not be distinguishable within a certain confidence interval. This issue can be even more pronounced in components, where several effects (e.g., environment, junctions, residual stresses) may be superposed. There is a need for accurate and reliable testing methods, able to assess the strength in components for a given geometry, loading, and environmental configuration.

In previous work of some of the authors, a novel testing methodology—the B3B method—was proposed as a candidate to mitigate such measurement uncertainties and provide reliable strength measurements applied to real components (see Fig. 2).

The biaxial strength of the disc- or plate-like specimens can be determined using a miniaturized B3B fixture (Fig. 2a), especially built in-house to match the dimensions of the given component. In the B3B method, a rectangular plate (or a disc) is symmetrically supported by three balls on one face and loaded by a fourth ball in the center of the opposite face (see Fig. 2b), generating a very well-defined biaxial stress field [25, 26]. A preload of a few N is applied to hold the specimen between the four balls. The load is increased until fracture occurs, and the fracture load, P, is used to calculate the maximum tensile biaxial stress, σ_{max}, in the specimen at the moment of fracture, according to:

$$\sigma_{\max} = f \cdot P/t^2 \quad (3)$$

where t is the specimen thickness, and f calculated using finite element (FE) analysis is a dimensionless factor, which depends on the geometry of the specimen, on the Poisson's ratio of the tested material, and on the details of the load transfer from the jig into the specimen [9].

In the following, the strength distribution of two functional substrates and components will be analyzed: (1) a silicon-based semiconductor die and (2) an LTCC. Samples with very similar geometry and functional features (e.g., metal interconnects, top metallization) as those found in real components were fabricated and tested for the study.

A. Silicon-Based Semiconductor Dice

The embedding of silicon dice into PCBs is an established process in the packaging industry [27]. During the assembly and lamination processes (die attachment, thermal pressing, and cooling down), thermally induced stresses occur that can lead to failure of the dice and/or warpage of the package [28, 29]. Typical embedding components are for instance Si- or GaAs-based semiconductor dice.

Due to the brittleness of the embedded components (e.g., $K_{Ic,Si} \approx 1.0$ MPa·m$^{1/2}$ [30]), the force required to fracture them can be of the order of a few Newton (see details in [31, 32]). An example of such miniaturized dice ($2 \times 2 \times 0.12$ mm^3) is shown in Fig. 3. One side of the die (upper side) consists of pure silicon (Fig. 3a), whereas the other side (bottom side) is covered with patterned Cu pads and Al interconnects (Fig. 3b). The thickness of the Al interconnects and Cu contact pads is ~2.5 μm and 8 μm, respectively; the diameter of the Cu pads being 220 μm. More details on the exact geometry can be found in [31].

To analyze the effect of surface features on the strength of the Si chips, both sides were tested under biaxial bending using the B3B method. Despite the deposition process and related residual stresses in the different layers, the samples were relatively flat and thus appropriate for testing.

B. LTCC Substrate and Component

The substrate (containing glass and ceramic) employed to fabricate the LTCC specimens of study consists of ~40% of Al_2O_3 ceramic filler and 60% of several glasses containing Ca, Na, Si, K, B, and Al, where the crystallization degree after sintering exceeded 90%. Microstructural characterization of the bulk material can be found elsewhere [22]. The processing route employed was tape casting of commercial LTCC tapes (panels of ~$100 \times 100 \times 0.45$ mm^3), provided by the company EPCOS OHG (TDK Corporation), Deutschlandsberg, Austria. The cosintering was performed in a furnace at 850°C. After sintering, rectangular plates of ~$11.0 \times 9.7 \times 0.45$ mm^3 were cut from each panel. The components were simplified in terms of their geometry to better understand the effect of metallization and/or vias on the mechanical strength. In addition to bulk material without metallization as reference material

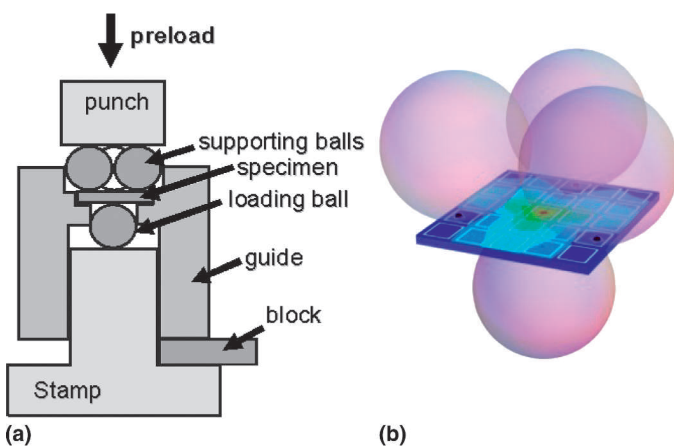

Fig. 2. (a) Schematic diagram of the B3B test for biaxial testing and (b) FE simulation of the stress distribution in the plate during loading.

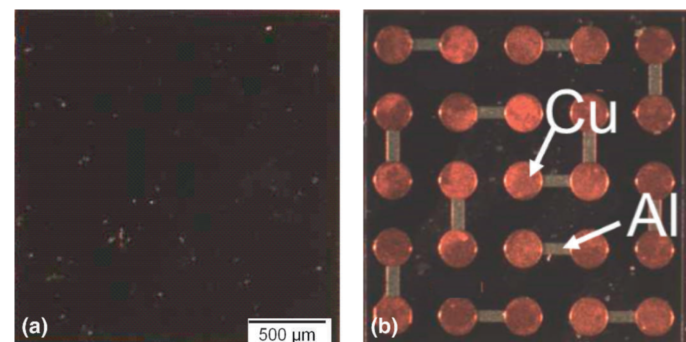

Fig. 3. Silicon dice for embedding into PCBs: (a) upper side with pure silicon and (b) bottom side with patterned Cu pads and Al interconnects.

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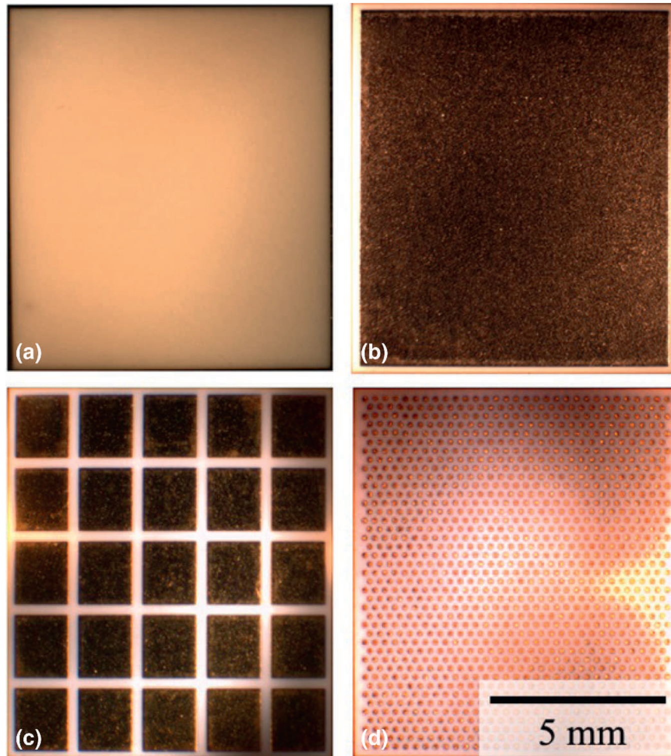

Fig. 4. Samples with different metallization at the substrate top surface: (a) bulk without metallization, (b) bulk with full metallization layer, (c) bulk with contact pads, and (d) bulk with cylindrical vias of 100 μm diameter and 50 μm depth.

(Fig. 4a), three LTCC samples with different surface metallization were fabricated:

1. MT: bulk LTCC with a full metallization layer of ~10 μm on top of the substrate (Fig. 4b).
2. CP: bulk LTCC with contact pads of 1.5 × 1.8 mm and ~10 μm thickness, covering the 75% of the top surface (Fig. 4c).
3. CV: bulk LTCC with cylindrical vias on the top with a diameter of 100 μm and a pitch of 300 μm, with a depth into the material of ~50 μm (Fig. 4d).

To discern the effect of surface metallization (e.g., contacting pads or cylindrical vias) and the effect of the environment on the strength of components, a novel experimental approach was attempted. Biaxial strength tests were performed in two different environmental conditions: (1) in water and (2) in dry silicon oil bath to reproduce high and low relative humidity (RH) conditions, respectively. In both cases, the samples (as described in Fig. 4) were placed in the B3B fixture and the corresponding fluid (i.e., water or silicon oil) was pumped into the specimen holder to fully cover the specimen during the entire loading. The temperature was maintained constant for all tests, i.e., 22 ± 2°C. The number of specimens tested for each sample ranged between 15 and 30, for statistical significance. The tests were conducted under displacement control at a constant crosshead speed (i.e., 0.1 mm/min) using a universal testing machine (Zwick Z010, Zwick/Roell, Ulm, Germany).

Strength Results

Fig. 5 shows the results of B3B tests conducted both on the Si-side and the metal-side of single-crystalline Si chips. Measured data are represented in a Weibull diagram where the failure stress, σ_f, *cf.* eq. (1), is plotted versus the probability of failure, F. The scale chosen in the graph allows representing Weibull-distributed data as a straight line, according to EN-843-5 [15]. The distribution for the pure silicon side and metallized side was collected on samples of 58 and 30 specimens, respectively. This sample size ensures good statistical significance for the Weibull analysis [7].

The results clearly show a difference in the characteristic strength and strength variability between specimens tested either with the metallized side under tension or the silicon side under tension (*cf.* Fig. 5). Values of characteristic strength, σ_0, on the Si-side were more than two times higher than on the metal-side ($\sigma_{0,\mathrm{Si}} = 3{,}529$ MPa versus $\sigma_{0,\mathrm{Me}} = 1{,}430$ MPa), whereas the Weibull modulus, m, was much higher on the metal-side ($m_{\mathrm{Me}} = 12.3$ versus $m_{\mathrm{Si}} = 2.6$). Since the only difference between the two cases is the side put under tension, it seems obvious that there is a strong effect of the deposited metal contacts on the overall strength behavior of the material.

The rather low Weibull modulus of the Si-side testifies a high dispersion of the failure strength and is in agreement with values obtained on well-etched Si-wafer surfaces [32-34]. The relatively high Weibull modulus for the metallized samples can be ascribed to the presence of edge cracks (precracks) in the proximity of the metallization caused by local stress intensifications during bending and the presence of residual stresses generated during fabrication of such multilayer structures. Such precracks may have the length of a functional layer and

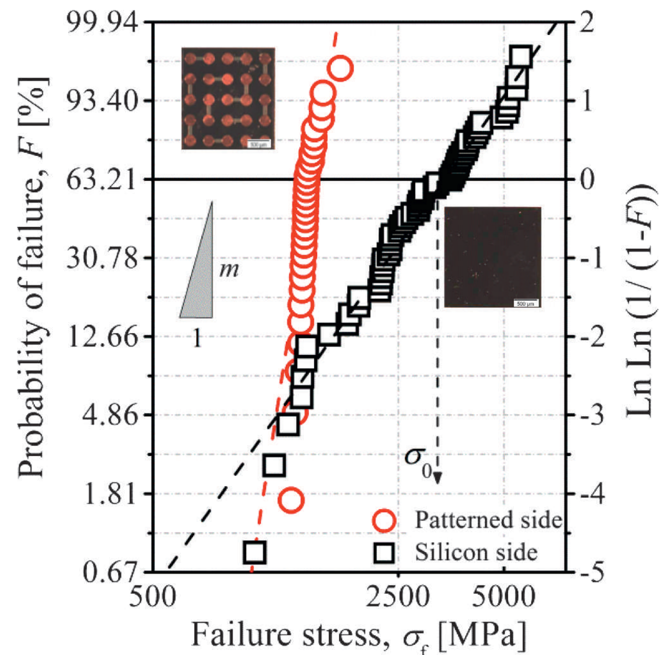

Fig. 5. Strength distribution of pure and metallized silicon dice tested under biaxial bending using the B3B method [31].

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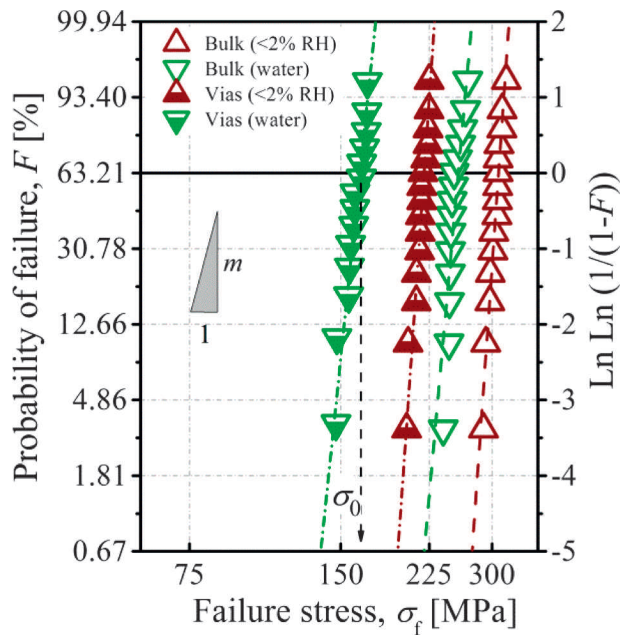

Fig. 6. Strength distribution of LTCC samples (bulk or with vias) tested under biaxial bending using the B3B method in two environments (water or dry oil with very low RH).

constitute the critical defects determining the failure of the metallized component. Further details on the onset of cracks in this type of specimens can be found in [35].

Fig. 6 shows the results of B3B tests conducted on (1) bulk LTCC samples and (2) LTCC samples with metallized vias in two environments: (1) water and (2) dry oil with an RH of <2%. Measured data are represented in a Weibull diagram, as in Fig. 5. The data were collected on four samples with 15 specimens each. The data fit (straight lines) showed a Weibull behavior in all four cases. The corresponding Weibull parameters along with the corresponding 90% confidence intervals can be found in [36]. Other sets of data corresponding to contact pads metallization MT and CP can be found in [36]. For the sake of simplicity, only bulk samples and CV samples will be analyzed in the following section.

It can be observed that the failure stress values follow a Weibull distribution, which is associated with the flaw size distribution in the specimens. Regarding the bulk LTCC samples, the failure stress values are lower when tested in water than in dry oil, i.e., $\sigma_0 = 257$ MPa in water versus $\sigma_0 = 309$ MPa in oil. This is associated with "degradation mechanisms" acting during mechanical loading in humid environments (SCCG), as has been reported for different LTCC materials [20-22, 37]. The SCCG of defects in the bulk samples during loading in water diminishes the strength (~20%) as compared with testing in dry conditions for the same loading rate. Concerning the samples with vias, a different situation is found, which reveal not only an effect of the environment (i.e., $\sigma_0 = 165$ MPa in water versus $\sigma_0 = 220$ MPa in oil) but also a negative effect of the vias on the strength, compared with substrate (bulk) material; i.e., strength can be reduced up to 40% compared with bulk material.

Summary

In summary, it has been shown that localized biaxial testing using the B3B method performed in different environments can be used as methodology for reliability assessment as well as to quantify the effect of surface features on the strength of functional brittle components. Surface metallization such as cylindrical vias or contact pads can become weak points in the design, affecting significantly the strength and reliability of components. In addition, environmental strength degradation due to the subcritical growth of defects during loading should be taken into account for lifetime prediction models of functional components.

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