Every solar cell is an original: laser marking of silicon solar cells yields new opportunities in quality control

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ABSTRACT

A major challenge for the solar industry over the next few years is the reduction of production costs on the road to grid parity. Capacity must be increased in order to leverage scaling effects, production and cell efficiency must also be enhanced, and the industry must focus on intensified process optimization and quality control. Laser marking can make a key contribution to fulfilling these requirements. As hard physical coding, laser marking is applied to the raw wafer at the start of the manufacturing process, making each solar cell traceable along the entire value chain and over its whole lifetime. This paper presents Q-Cells' laser-supported process for coding each individual solar cell (European patent pending), which will require transition work at the laboratory stage before the company's innovation is ready for mass production.

Traceability by means of a data matrix code

Laser marking as a means of identifying raw silicon wafers was first used in the semiconductor industry around 35 years ago. Early markings comprised characters that were legible by humans, and in the mid 1980s, a method using bar codes was developed. According to a study conducted by the Fraunhofer Institute for Solar Energy Systems (ISE), the method employed in the semiconductor industry to mark products involves a two-dimensional matrix code in line with the Semi T2-0298E standard. In solar cell manufacturing, however, the use of laser bar codes on wafers would require a somewhat larger area in comparison with dot matrix codes. Since the code is to be written on the front of the cell, it would encroach on the finger grid.

The new code is a two-dimensional industry standard data matrix code called Data Matrix ECC200, which is a highly robust de facto industry standard. Reed-Solomon error correction allows for around 25% redundancy in a matrix in which the outer lines of the code are required for better code identification by the reader. Typical matrix sizes are 8 × 32, 14 × 14 or 12 × 26. The actual data content is scrambled and strategically distributed over the whole area to achieve a high level of robustness against missing dots, disturbance or code corruption. The capability and structure of error correction is particularly important in the solar industry (for example, if solar cell fingers are printed over the code).

This tiny code on the front of a solar cell ensures that each cell can be recognized by machines and is, therefore, traceable. The code remains readable even when the cell is integrated in the finished solar panel and survives all processing steps such as texturizing, the application of anti-reflex coating and firing. Unlike laser bar codes on semiconductor wafers, which require dedicated areas to be left free to accommodate them, the marking can be applied in the active area of the solar cell without impairing the solar cell's power generation capability. This fundamental difference represents a huge leap forward and is a massive benefit to the photovoltaic industry.

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Dot matrix codes can not only be written and read easily and reliably, but can also store a huge volume of data. This makes them ideal for ensuring traceability, something that has been proven as vital time and again in the mass production of literally millions of wafers over the past few years. Alternative methods include laser marking at silicon ingot level, which creates patterns on the edge of the wafer, or wafer identification through the unique surface characteristics of each multicrystalline wafer.

Ingot marking, for example, is an extremely simple method of marking wafers. In this process, wafers are marked at the beginning of the process and the wafer position in each ingot can be determined, even if the ingots or blocks have been sliced. This is achieved through the application of a bar-code-like pattern on the side of the block. Once the wafers have been sliced, the edge of each wafer bears a unique pattern. To enable this data to be reliably read out during mass production, either all four sides of a block need to be marked or reading equipment must be installed at each edge of the wafer since wafers turn through different positions as they pass through various wet benches and manufacturing processes.

Since the data volume is much less than that of data matrix codes, it is impossible to assign a unique serial number to each cell in order to achieve end-to-end traceability over a solar cell's lifetime; an ingot index is used instead, which is a simple method of allowing wafers to be traced back to their ingots and their position therein. Determining whether ingot marking can help to trace solar panels and whether the markings can be read out reliably will require further serious investigation. Since the marking is applied to the extremely fragile edge of the cell, however, Q-Cells has chosen not to continue developing this process for mass production in order to minimize the breakage rate – a must for high-yield solar cell production.

Another method of identifying and tracking solar cells is to exploit the unique surface characteristics of each wafer, a similar method employed by face or iris recognition equipment in modern airports. Since the pattern on adjacent sliced wafers is very similar, an extremely high picture resolution would be required. In turn, this would require a much larger volume of data to be stored in comparison with the far easier process of reading a number encoded in a dot matrix code. Another reason this method has not been further developed for mass production is that it is unsuitable for monocrystalline wafers because, with their homogenous surface, they do not offer any meaningful distinguishing characteristics to enable unique identification.

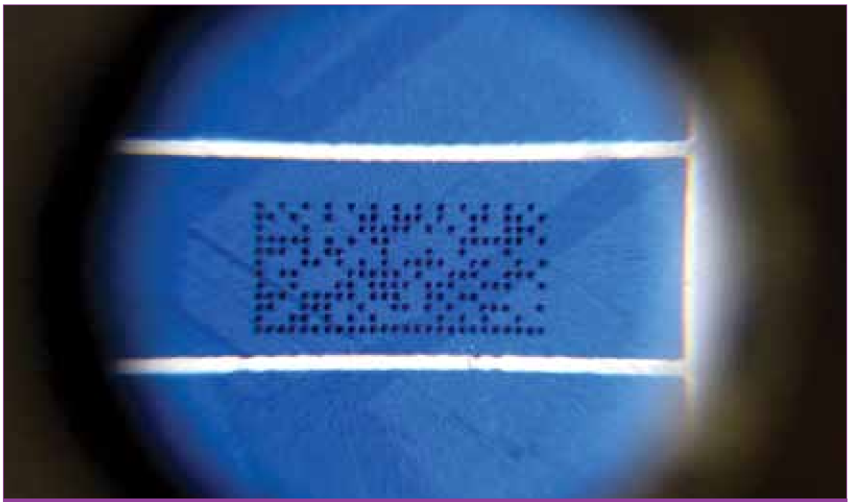

Figure 1. Laser marking on solar cells.

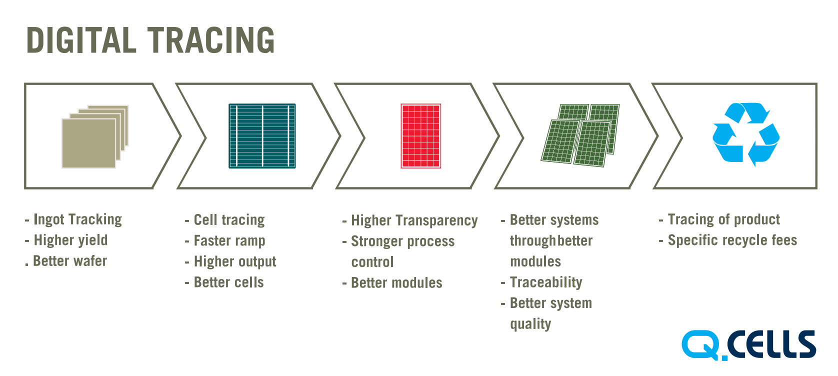

Figure 2. Digital tracking by laser marking across the entire value chain of the solar industry, from raw wafer to PV recycling.

In short, factors such as cost, throughput, convenience, reliability, the volume of data they can hold as well as the availability of both reading and writing equipment make dot matrix codes, applied to the front of cells, the ideal solution.

Laser marking: benefits for the PV manufacturing chain

Laser marking has proven to be a highly effective means of enhancing quality and achieving process stability. The digital marking of each individual solar cell allows maximum traceability across large sections of the photovoltaic value chain – from the silicon raw wafer to solar modules and systems – meaning that production steps can now be tracked in great detail. The process increases the transparency of each step, thereby enabling employees to know exactly which raw materials and manufacturing processes were used.

Laser marking allows manufacturers of silicon solar wafers to obtain information about the wafer and the ingot from the parameters of a solar cell. The findings from analyses of the production materials and processes used are directly implemented in subsequent optimization measures, thereby enabling a higher yield and higher-quality wafers. Tracking the solar cell manufacturing process provides information on the machines and procedures used during production. The learning effects achieved enable cost efficiencies and a quicker ramp-up phase at new production sites. Ongoing process control and quality optimization not only results in a higher production yield for manufacturers of solar cells and solar modules, but also improves overall system performance.

Application of the marking to the front of the cell, in particular, allows for the tracing of cells in modules even after they have been laminated, machined or even installed in a solar power plant. In the spirit of developing an environmentally-friendly range of products, laser marking data can provide useful information about recycling solar panels; even decades after the recycling of these cells and modules, this marking can identify exactly which materials were used in the production of the cells.

Application of laser markings on crystalline solar cells

A key aspect of laser marking is a clearly defined process for writing the data matrix code. The precise placement of the laser marking code can greatly improve readability. Of course, the placement of the code in relation to the finger layout (see Fig. 2) is extremely important, but the active area in which the laser writes the code and the field of view in which the data matrix reader can reliably detect the code also need to be taken into consideration. The best results have been achieved by placing the code near the centre of the solar cell, taking into account bus bar and finger layout.

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Great care needs to be taken to ensure that laser markings do not affect the electrical parameters of a cell, for example through the effects of shunts that could occur if the laser markings are 'burned' too deeply into the silicon wafer rather than being written within a specified range of permitted depths at surface level. For this reason, parameters such as laser power, wavelength and duration of writing need to be precisely defined and verified by means of practical testing. Also, despite the fact that the laser markings should preferably be rather shallow, they should still be deep enough to resist wet bench processes in solar cell production. The best results have been achieved with Nd:YAG lasers operating at a wavelength of, for example, 1,064nm with pulse durations of between 20ns and 50ns, power of between 5W and 30W, and creating dots 100µm in diameter and between 10µm and 30µm deep (before etching). Tests (see Fig. 3) have confirmed that without an optimized writing process, the readability of laser markings falls short of mass production requirements, which far exceed 90%.

Equipment for reading laser markings

To achieve the highest possible reading rates, optimized laser markings are essential. Various experiments have been conducted involving inspection systems and light sources from different suppliers. As solar cells move along the production line, their surfaces change in response to the etching, oxidation and heating processes that they undergo, which meant that, in this case, the reading equipment needed to be optimized. While the light source in conventional dot

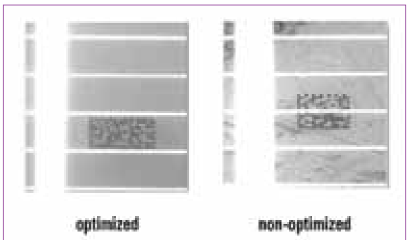

Figure 3. Optimized and non-optimized code writing laser markings with different laser parameter.

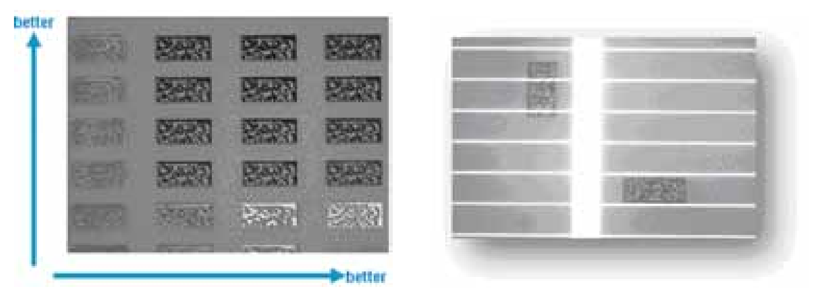

Figure 4. a) Impact on readability through specifying the right process for *writing* laser marking code; b) impact on readability through specifying the right process for *reading* laser marking code.

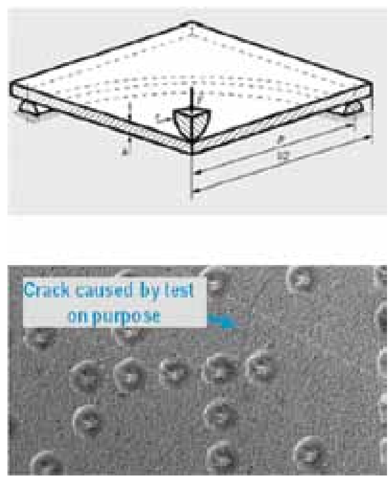

Figure 5. Investigation of solar cells' stability. The 'ball-on-ring' test provided evidence that breakage cracks have no correlation with laser marks.

matrix readers (DMR) was provided by a blue LED, it was discovered that the reading rate could be improved by using a red LED, particularly downstream of wet bench processes. Readability was further improved by optimizing the shutter speed in order to regulate the exposure time. Figs. 4a and 4b illustrate the huge difference in readability following optimization of the write process (Fig. 4a) and the read process (Fig. 4b) for laser markings.

The readability of laser markings depends on the optimisation of write and read processes – and it is clear that both measures are essential in order to achieve the best possible results in industrial mass production. Readability was further improved by optimising the shutter speed in order to regulate the exposure time. Optimization is achieved through iterative learning, a process that improves as the production volume increases.

Mechanical stress test

Another key advantage of implementing laser marking technology in industrial mass production is not only the stability of the process during high-volume production, but also the fact that the technology has zero impact on the product itself. Great care has been taken to ensure that this new technology does not affect cell handling, cause any breakages or microscopic cracks or have any impact on production yield. Tests were conducted in which wafer stacks containing between 100 and 300 wafers each were examined for microscopic cracks following both manual and automatic handling. The wafers were carried and moved around in an actual mass production environment along with their non-laser-marked counterparts. Following an initial examination for microscopic cracks, the wafers were transported and handled in such a way as to simulate the stress levels they would be subjected to during regular production. A 'twist test' carried out with around 70% of the force of a pre-determined breakage force was also performed to identify any microscopic cracks.

> "Any cracks that did occur were not due to the laser marking because they occurred between the individual markings rather than across them."

Further investigations were conducted by the independent Fraunhofer CSP institute, which used the 'ball-on-ring' method to test solar cell samples with a thickness of 160μm and different marking depths (see Fig. 5). It was evident from these tests that any cracks that did occur were not due to the laser marking because they occurred between the individual markings rather than across them. This confirmed that the laser markings do not have any significant effect on breakage strength in their vicinity. Fig. 6 shows the distribution of the force required to break a solar cell, in relation to the depth of the laser markings.

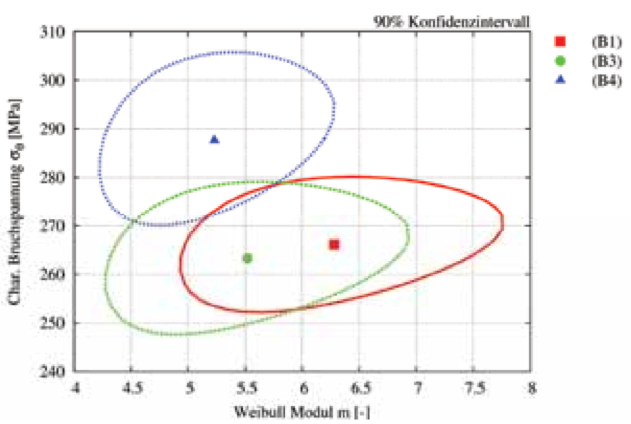

Figure 6. Investigation of solar cells' stability. The force required to create breakage shows no correlation with laser marking. Red: no marks; green: flat marks; blue: deep marks.

Data matrix code

The new code is a two-dimensional industry standard data matrix code called Data Matrix ECC200, which is a highly robust de facto industry standard. Reed Solomon Error Correction allows for around 25% redundancy. In a 14 × 14 data matrix, 12 × 12 dots are reserved for data. The outer lines of the code are required for better code identification by the reader. Typical matrix sizes are 8 × 32, 14 × 14 or 12 × 26. The actual data content is scrambled and strategically distributed over the whole area to achieve a high level of robustness against missing dots, disturbance or code corruption. The capability and structure of error correction is particularly important in the solar industry (for example, if solar cell fingers are printed over the code).

Fig. 7 shows the new IOSS reader along with its analysis software. The red dots indicate the readability status of the code on the screen. As the code is available in various sizes (e.g. 14 × 14, 12 × 26 or 8 × 32), the system was chosen on the basis of various parameters such as the finger pitch of a solar cell, its capability to store different volumes of data, the time required to write the code and possible space constraints. To achieve the best possible results in mass production, Q-Cells conducted a number of experiments to determine the optimum size and placement of the code on the surface of the solar cell. Fig. 9 shows

Figure 7. Example of an industrial type data-matrix reader from IOSS GmbH (left). This reader has adjustable light and camera parameters in order to optimize readability, which is indicated by the red dots in the right-hand image.

an example of an actual implementation of ID laser marking. The encoded information can contain information such as the producer identifier, check digit, year/week, marker and running number.

Success story

Fig. 10 shows one actual example of a scenario where improvement of the diffusion process was brought about in Q-Cells' production. Sheet resistance is usually the control parameter used to check that the emitter definition is correct. However, as pictures a) and b) in Fig. 10 show, there is no indication of any efficiency dependence over the boot position. Only information gained at the cell tester can enable the engineers to develop improved recipes with higher efficiency and therefore maximum cell performance by creating a closed feedback loop, helped in this goal by laser marking. Although the ability to link cell tester data without laser marking is theoretically possible in the ideal IT production environment, the process either does not yet exist, is unaffordable or requires considerable testing. This would entail extra manpower, precisely specified reference material, and disruptions to ongoing production. Thanks to laser marking, however, such

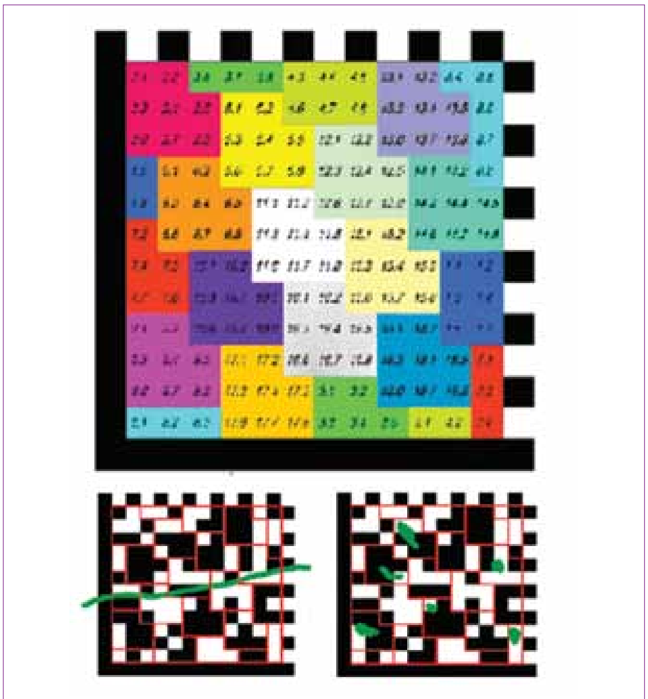

Figure 8. Distribution of the data matrix code. Top picture shows distribution of data across the data matrix for best reliability and recovery. The lower two pictures are examples of correctable and non-correctable code.

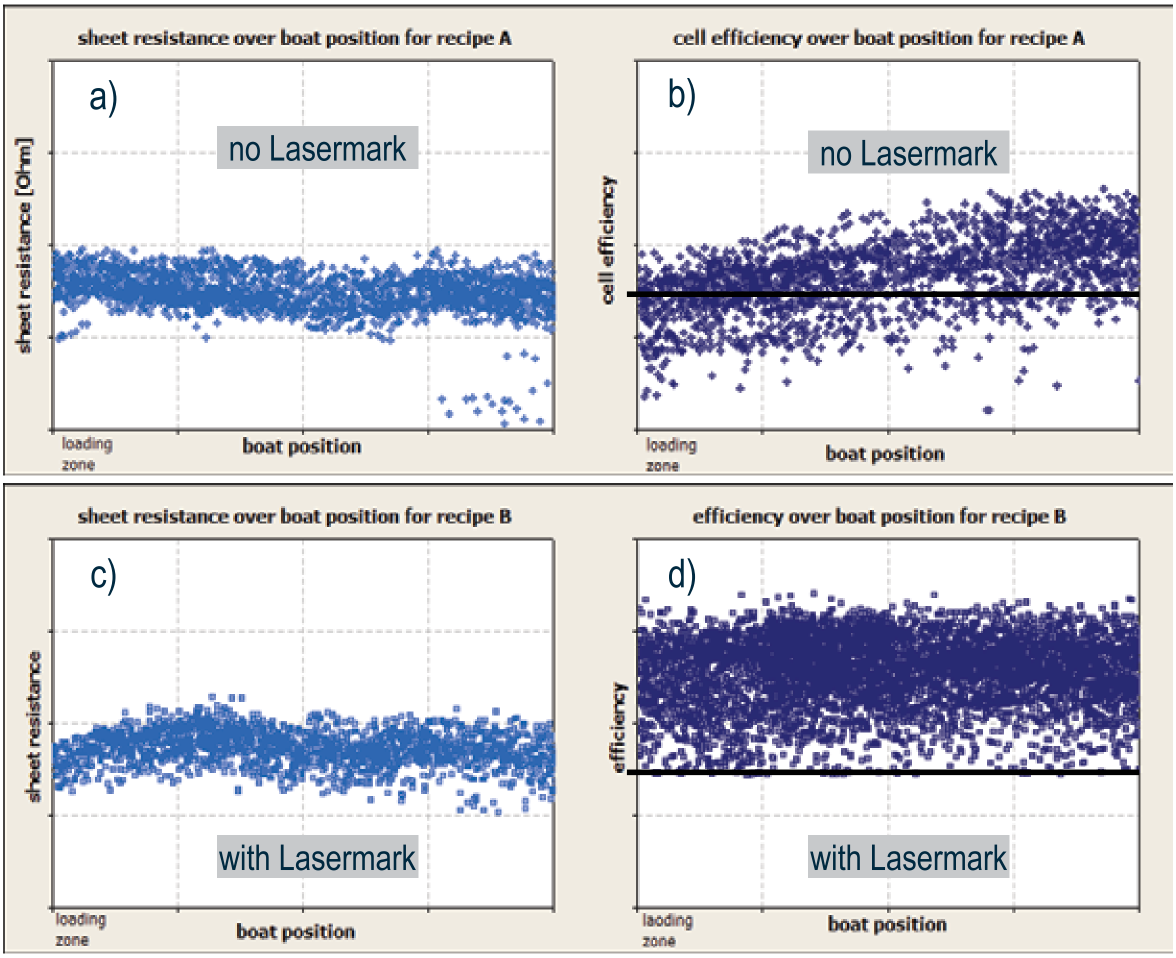

Figure 10. Improvement of the diffusion process at Q-Cells using laser marking.

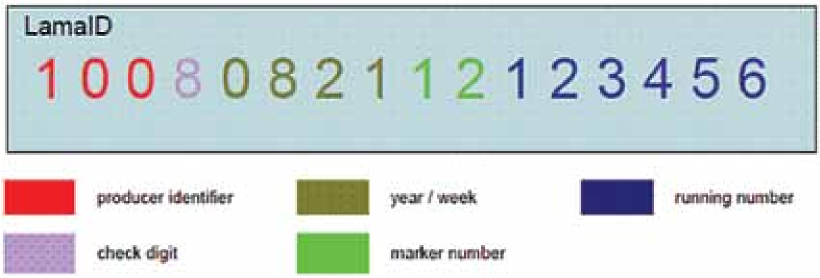

Figure 9. Example of the content of a data matrix.

improvements can be achieved much more easily by using equipment from different lines in parallel with a much greater degree of statistical reliability and without disrupting ongoing production.

Processes for increasing sustainability in the PV industry

The laser marking of solar cells with a unique signature is an unprecedented step forward. The process makes a valuable contribution not only to automation and cost reduction, but also to ensuring sustainable environmental protection in the industry. It also allows end-to-end traceability, which has long been standard in other branches (e.g. the automotive sector). Containing the manufacturer ID and the product specifications, laser markings also help speed up the active recycling process of reusable solar components. The unique numeration of each solar cell offers additional advantages for customers too. For example, manufacturers can offer a guaranteed and verifiable quality standard. It also prevents product forgeries and allows complaints to be processed more quickly and efficiently.

Laser markings on solar cells – hard codes as unique numbers permanently embedded in the silicon over the entire product lifetime – not only allow manufacturers to offer products of superior quality, but also underline the sophisticated technological approach of cell suppliers in the PV industry.

About the Author

Peter Wawer studied electrical engineering at the TU Berlin, focusing on lifetime measurements of silicon crystals, and completed his Ph.D. work on thin crystalline silicon solar cells. In 1997, he began a career as a development engineer at Siemens Semiconductors in Dresden, progressing to the Infineon AG headquarters in Munich in 2004, where he held various positions predominantly in the area of technical management. Since November 2008, Peter Wawer has been responsible for the overall development activities in the core business of Q-Cells SE and is member of the board of Solarvalley Saxony-Anhalt e.V.

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