Flexible Solar Cells for Micro-Autonomous Systems Technology

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ABSTRACT

Insensitivity to edge recombination is observed in GaAs-based InAs/InGaAs quantum dots-in-a-well (DWELL) solar cells by comparing their current-voltage (IV) plot to GaAs control samples. The edge recombination current component is extracted by analyzing devices of different areas and then compared to DWELL cells of comparable dimensions. The results demonstrate that GaAs-based solar cells incorporating a DWELL design are relatively insensitive to edge recombination by suppressing lateral diffusion of carriers in the intrinsic layer, and thus promising for applications that require small area devices such as concentration or flexible surfaces. Preliminary studies on the integration of these cells onto flexible surfaces such as Kapton and nanopaper are discussed including weight considerations for all the integrated materials.

Keywords: quantum dot, photovoltaics, flexible solar, micro-autonomous systems

1. INTRODUCTION

Commercial thin-film flexible photovoltaics are paving the way to low-cost electricity. Organic, inorganic and organic-inorganic solar cells are deposited over flexible substrates by high-throughput (often roll-to-roll printing) technologies to afford lightweight, economic solar modules that can be integrated into various surfaces. Current conversion efficiencies under standard conditions are in the 3-15 % range for potentially flexible, thin film devices. Meanwhile heavy, stiff, and fragile inorganic materials can exceed 30% efficiency. A review of current commonly-available flexible thin-film solar technology shows that the best performing products, PowerFilm (amorphous Si) and thin-film CIGS, demonstrate a power density of ~0.13 Watt/gram. For small DoD platforms with constrained size and weight limitations, it is highly desirable to substantially increase the power density by at least an order of magnitude by utilizing high efficiency materials in a light, flexible architecture. The objective of our flexible thin-film solar cell research is to realize a specific power > 2 Watt/gram and to integrate these cells onto novel, lightweight membranes suitable for wings. The research presented here is focused on maintaining high efficiency in rigid, but very small area solar cells that can be individually arrayed onto flexible surfaces. The candidate semiconductor technologies that we have analyzed for this application include Quantum Dot (QD) solar cells and conventional bulk GaAs devices.

QD solar cells have been actively investigated recently since they have been theoretically shown to have the potential to realize high power conversion efficiencies (>60%) with an optimized intermediate band design or to increase the short circuit current by extending the absorption edge further into the infrared (IR) [1-4]. However, very little research has analyzed the effect the dots have on the transport or recombination effects in the device. In this research, the I-V characteristics for 6-stack InAs "dots-in-a-well" (DWELL) [5-7] solar cells are discussed and compared to GaAs cells. The test data collected for the QD devices are consistently better than the GaAs control cells as the area of the device is reduced.

2. DEVICE DESIGN AND FABRICATION

A QD is a semiconductor whose excitons are confined in all three spatial dimensions. As a result, they have unique optical and electronic properties that can be exploited. Figure 1 shows the DWELL structure grown by molecular beam epitaxy (MBE), where the indium arsenide (InAs) QDs are fully embedded in the InGaAs quantum wells. The DWELL structures have been successfully grown since 1999 [5] at the University of New Mexico, and have been applied in

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various QD devices with state-of-the-art performance, such as low-threshold current-density diode lasers [6] and high-responsivity, long-wave IR detectors [7].

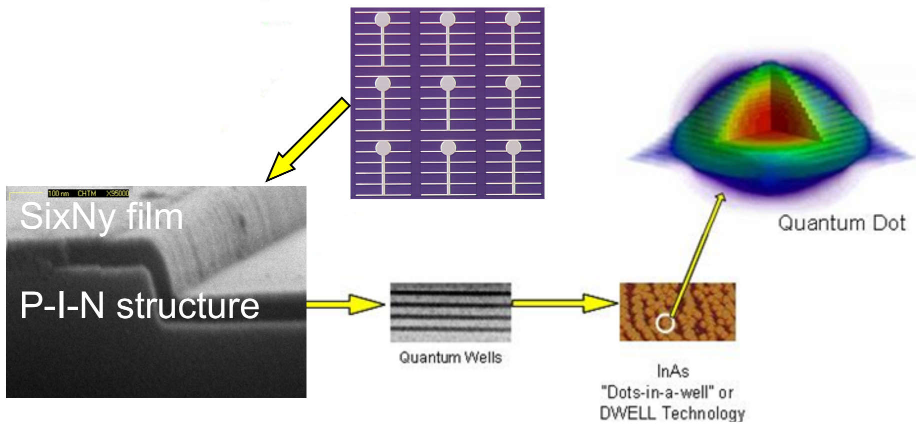


Fig. 1. Counter clockwise from the top: (a) Processed solar cell image, (b) SEM image of the solar cell's cross section. (c) DWELL structure in the intrinsic layer. (d) Atomic force-microscope image of the QDs. (e) 3D image of a single dot.

InAs self-assembled QDs with surrounding InGaAs quantum well (QW) layers were incorporated into the intrinsic region of a GaAs *pin* diode. The epitaxial growth sequence followed the following recipe: after the growth of a GaAs buffer layer and lowly dope p-GaAs base layer, multiple stacks of InAs QDs embedded in InGaAs thin films were grown by self-assembly with a slow growth rate of ~0.1 monolayers/s, which provides high dot quality and large dot size. Then, a wide band gap n-AlGaAs window layer followed with a n-GaAs cap for ohmic contact formation. The solar cell structure is a *pin* diode, with a 200 nm i-layer. The control cell structure is similar to the QD one except that there are no InAs dots or surrounding InGaAs quantum wells. As for DWELL structure shown in the schematic diagram in Fig. 2, there are six layers of InAs quantum dots with a bandgap of ~1100 nm grown within the undoped i-region. The epi structures were grown on p+ type 2" wafers. The total QD density for the DWELL cells is $\sim 6\times10^{11}$ cm^{-2}.

Due to the high dot density (1×10^{11} cm^{-2} per stack) and the DWELL collection mechanism, the effective ''area'' seen by the incident photons is larger in the DWELL structure in comparison to a conventional InAs QD structure. This improves the spectral response and conversion efficiency of the solar cells. In addition, the DWELL cells have unique carrier transport properties that are introduced into the solar cell device by the QDs [8]. It is well known that quantum dot structures efficiently confine carriers and thus inhibit the lateral spreading of current to the perimeter of a device where edge recombination can dominate. Consequently, QD solar cells are potentially insensitive to the edge or surface recombination currents that would normally set a floor on the minimum cell area. As a result, the DWELL cells are promising for concentration and flexible surface applications for which shrinking the size of the device and maintaining high charge collection efficiency are of paramount importance.

The control and DWELL solar cells were fabricated simultaneously to keep all the process the same. The devices are fabricated with three different area dimensions ($5\times5mm^2$, $3\times3mm^2$, $2\times2mm^2$). After patterning, the samples are placed in an e-beam evaporator for top n-metal contact of Ge/Au/Ni/Au. After lift-off, the samples are placed back into the e-beam evaporator for the bottom p-metal contact of Ti/Au. A 270-nm deep mesa is dry-etched by inductively coupled plasma (ICP) etcher to the intrinsic region to separate neighboring solar cells. Finally, an anti-reflective coating (ARC) layer is deposited using plasma enhanced chemical vapor deposition to the front surface for reducing the reflection loss of the incident photons and improving the surface passivation. The ARC layer is 80-nm thick Si_xN_y with a refractive index ~2.0. The mesa is deliberately shallow which minimizes the device sidewall and potential recombination there. However, the shallow mesa exposes the device to lateral diffusion current that expands the perimeter of the cell around the *i*-region and nearby base. This process results in proportionally more of the current flowing at the edge of the device, even for the emitter. The DWELL structure inhibits this lateral diffusion, whereas the GaAs control cell does not.

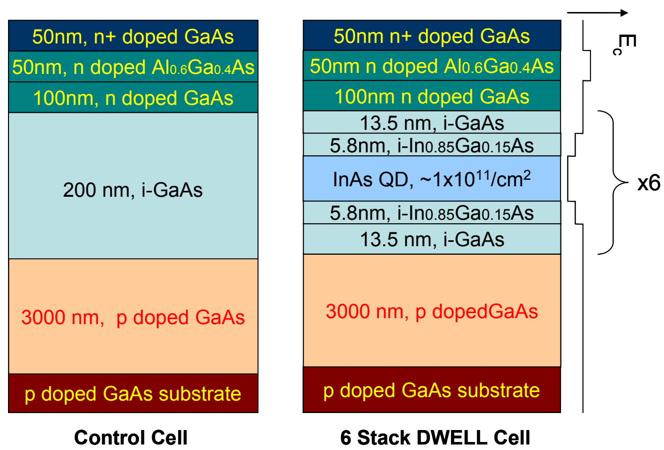


Fig. 2. Schematic diagrams of the GaAs and DWELL cell epitaxial structures. The DWELL design contains six-stacks of InAs QDs in InGaAs QWs.

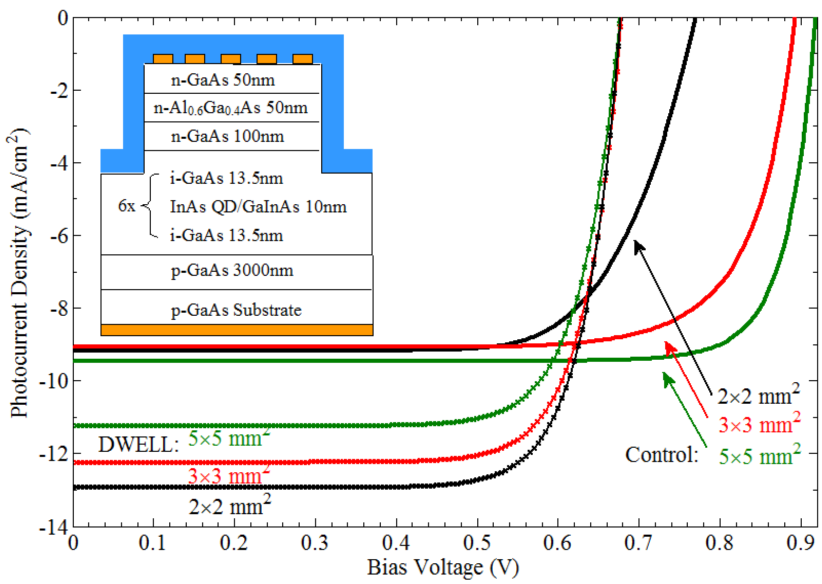


Fig. 3. Photocurrent of DWELL and GaAs control cell of different sizes (2×2 mm^2, 3×3mm^2 and 5×5 mm^2) under AM 1.5 global illumination. The inserted picture is the schematic diagram of the DWELL solar cell with six-stacks of InAs QDs embedded in InGaAs quantum wells.

3. EXPERIMENTAL RESULTS

For IV characterization, the cell is illuminated using an ABET Technologies 150-Watt Xe lamp. A filter is inserted between the source and cell to simulate the AM1.5G spectrum. The solar cell is connected to a Hewlett Packard 4155B parameter analyzer by a four-point probe approach to eliminate the series resistance introduced by the probes and the parameter analyzer. As shown in Fig. 3, the typical DWELL device exhibits higher J_{SC} while maintaining the same open circuit voltage (V_{OC}) for smaller areas. For the GaAs control cells, however, a smaller size that has a higher perimeter-to-area ratio makes edge recombination current dominant in these devices, and, thus, severely impacts their V_{OC} and efficiency. Here V_{OC} of the 2×2 mm^2 GaAs cell is 10% lower than the 5×5 mm^2 one as shown in Fig. 3 and Table 1. This is a direct result of the larger reverse saturation current density in the smaller GaAs cells. From the data summarized in Table 1, it is clear that the InAs DWELL cells are the preferred choice in terms of efficiency when the cell area is small. From the data summarized in Table 1, it is clear that the InAs DWELL cells are the preferred choice in terms of efficiency when the cell area is small. These results will be considered in the future during the integration studies on flexible membranes.

TABLE 1: Measured short circuit current densities (J_{sc}), open circuit voltages (V_{oc}), and efficiencies of the GaAs control cells and InAs DWELL solar cells under AM 1.5G illumination.

Size	***J_{sc} (mA/cm^2)***		***V_{oc} (V)***		***Efficiency (%)***	
	Control	*DWELL*	*Control*	*DWELL*	*Control*	*DWELL*
5×5 mm^2	9.46	11.23	0.914	0.665	8.85	7.04
3×3 mm^2	9.08	12.23	0.890	0.670	7.61	7.79
2×2 mm^2	9.17	12.93	0.834	0.675	7.41	8.17

4. PRELIMINARY INTEGRATION ON FLEXIBLE SURFACES

We have studied the weight distribution including the photovoltaic devices for different hypothetical wing systems in a mico-autonomous flyer. Various wing membrane were considered as discussed below. It is assumed that the wing area is 20cm×15cm. The InAs DWELL solar cell is 400 ×400μm^2 and weighs approximately 1.38 grams at 10-μm thickness, excluding the contacts. The emitter contact (Ge/Au/Ni/Au: 260Å/540Å/200Å/3000Å) covers 20% of the top surface and weighs 0.0371 grams, and the base contact (Ti/Au/In: 500Å/3000Å/30,000Å) weighs 0.695 grams.

For the wing membrane, we evaluated three different materials:

1. Nano-paper (Nylon 66): 1.8 ×10^{-4} grams/cm^2, 1.5 μm thick, 8.1× 10^{-2} grams
2. Kapton: 1.42 grams/cm^2, 25 μm thick, 1.07 grams
3. Aluminum (Al): 2.7 grams/cm^2, 25 μm thick, 2.03 grams

Table. 2. The Comparison of the power, size, thickness, and weight for the different materials for the COMBAT wing membrane.

	Material	**Density (g/cm^2)**	**Size (cm^2)**	**Thickness (um)**	**Wing Membrane Weight (g)**	**Total Weight (g)**	**Power (W)**	**Watt/gram**
1	Kapton	1.42	15x20	25	1.07	2.08	4.3	2.1
2	Aluminum	2.7	15x20	25	2.03	2.8	4.3	1.5
3	Nano-paper (Nylon 66)	0.00018	15x20	1.5	0.081	1.32	4.3	3.3

The results presented in Table 2 indicate that a wing composed of Nano-paper (Nylon-66 jet-sprayed to a weight of 1 g/cm^2) presents the best solution for least total weight, resulting in a value of 1.32grams. The total weight of a wing composed of Kapton or Aluminum is 2.08 grams and 2.8 grams, respectively. Although the results show that Nano-paper made of Nylon-66 is a better choice due to its light weight, it is not always a practical choice due to material and processing limitations such as: 1) 200^{o}C maximum temperature 2) tears easily, and 3) handling difficulty. Instead, based on the technology that we have demonstrated to be practical for solar cell fabrication and system integration, we decided to use Kapton as the wing membrane which has the second best total weight (2.08 grams). This material is durable, can withstand high temperatures, and can be handled easily.

To study the effects of thinning down the solar cell on its performance, we investigated the solar cell characteristics at different thicknesses (385µm, 200µm, 100µm, 50µm, 20µm) after chemical and mechanical polishing. This experiment was conducted on multiple samples previously studied. The samples are listed as follows:

1. Run2609: control, 200nm i-layer
2. Run2752: control, 430nm i-layer
3. Run2611: 6 stack QD without strain compensation
4. Run2748: 6 stack QD with strain compensation

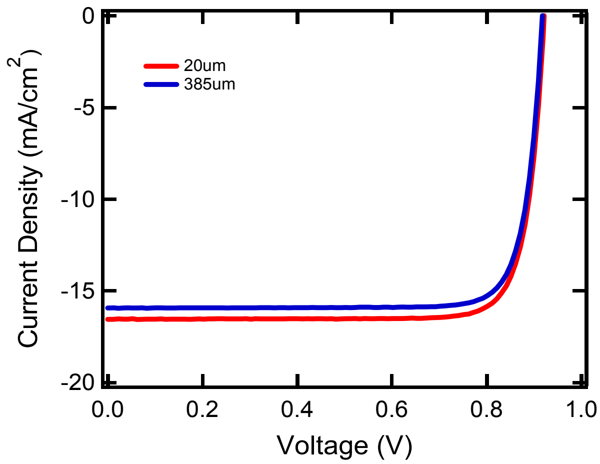


Fig. 4. Measured light I-V characteristics of the flexible thin film solar cell under AMG 1.5, 1 sun illumination, before and after the substrate thinning.

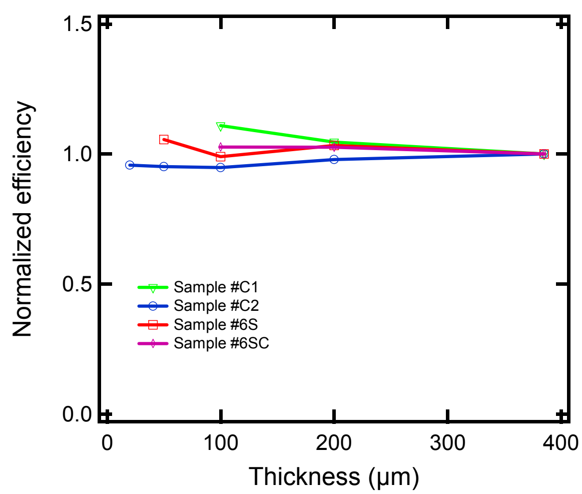


Fig. 5. Normalized efficiency for thin film solar cells at different cell thickness (385µm, 200µm, 100µm, 50µm, 20µm).

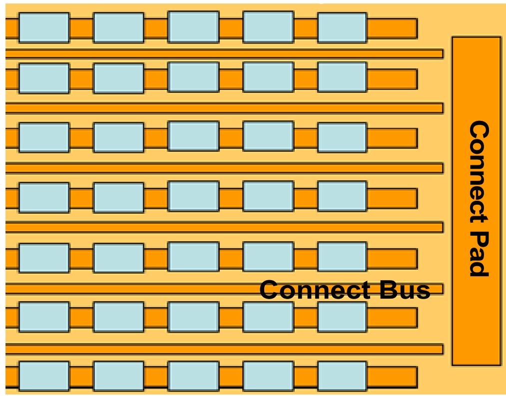


Fig. 6. Flexible InAs DWELL microcells arranged on a conductive seed layer that is evaporated onto a Kapton membrane.

Fig. 4 shows that the light IV for the flexible thin film solar cell before and after substrate thinning. The initial substrate thickness is 385 µm, and the final thickness after lapping and polishing is 20 µm. As can been seen from the Fig.4, the device performance has no any degradation as the device thickness was reduced down to 20 µm. Fig.5 shows the efficiency change as the sample thickness is thinned down to 20 µm. The initial power conversion efficiency for the InAs DWELL cell is 12-15% for a typical device size of 2x2 cm^2. The normalized average efficiency data shows that the value remains at approximately 1, indicating the device thickness does not affect the characteristics behavior of a solar cell down to 20µm. This is advantageous because the solar cell weight can be reduced with no efficiency penalty, which in turn can improve the watts/gram value.

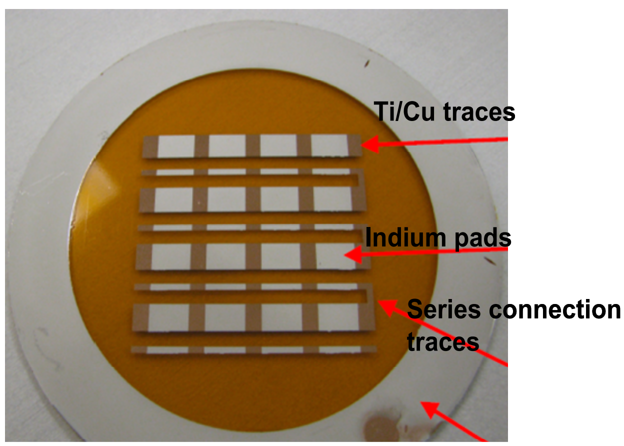
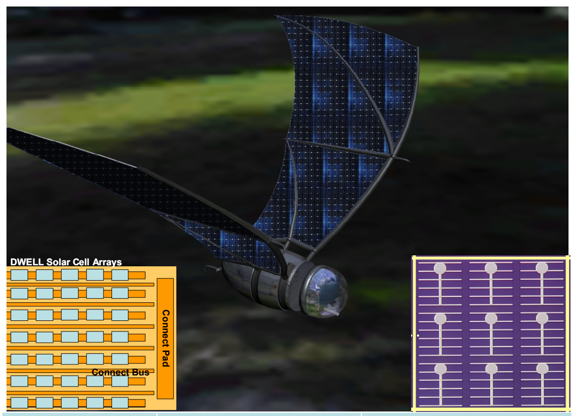


Fig. 7. The picture shows Kapton® mounted on aluminum rings with the connect bus bars used for mounting and current flow.

Conventional solar cells are bulky and rigid, but building lightweight, flexible cells come with trade-offs in efficiency and robustness. A new method for making flexible arrays of tiny solar cells could produce devices that don't suffer these trade-offs. Arrays of these microcells would be as efficient as conventional solar panels. As stated above, one solution for the need of flexible solar cells is to create an array of rigid dye onto a flexible Kapton substrate. Kapton is a commercially available plastic that can be purchased at very thin thicknesses. At 0.1mm thick Kapton is a very flexible material, light weight, and structurally strong enough to support the bonded dye. Kapton is a non-conductive material.

Therefore we need to deposit a conductive layer onto the Kapton to create electrical connection to the dye as well as for bonding purposes. Thin metal layers can easily be deposited onto the Kapton using an electron-beam evaporator. If deposited at the proper thicknesses, the conductive seed metal will adhere to the Kapton substrate and be flexible. Photolithography techniques can be implemented to control this metal deposition in a pattern desired for a combination of series and parallel connections. Our initial design for arranging the dye is shown in Fig. 6. The conductive strips in between the arrayed dye can be used for the top connection of the solar cells. For this design the dye can be arranged in virtually any manner desired, also the conductive seed layer can be patterned as desired for a combination of series and parallel interconnections. Clearly the small gaps between the rigid cells allow for the underlying Kapton substrate to flex without compromising the performance of the rigid solar cell die. Fig. 7 shows the image of Kapton mounted on aluminum rings to process the connect bus bars that are used for mounting and current flow. This approach allows us to use conventional, wafer-scale lithographic processing for the Kapton-related work. The conduction layer is e-beam evaporated Ti/Cu, and the indium pads are deposited by thermal evaporation, which is used for cold bonding of the microcells. The thickness for the Ti/Cu traces is 200/500 Å. The indium bonging pads is ~ 1 µm thick.

a)



b)

Parameter	Thin-film amorphous silicon (Powerfilm)	MAST GaAs-based QD solar cell with KAPTON membrane
Surface area	20 cm x 15 cm	20 cm x 15 cm
thickness	200 micron	5-10 micron
weight	9.2 gram	0.95-1.82 gram
Operating voltage	6V	6.8V
Operating current	200 mA	800 mA
Power output	1.2 W	5.4 W
Efficiency	4%	15%
Specific power	0.13 Watt/gram	3.0-6.0 Watt/gram

Fig. 8. Schematic diagrams of the MAST flyer and a summary of the performance metrics for its wing technology based on commercially-available amorphous silicon and future QD cell/Kapton approaches.

5. CONCLUSIONS

Flexible solar cells are currently being implemented using organic cells, amorphous silicon, as well as flexible arrays of rigid solar cell die. Organic solar cells possess benefits in being highly flexible and cheap in production. However, organic solar cells have a very short lifetime and low efficiency (~5%). Amorphous silicon also has the benefit of being flexible and cheap (as compared to solar cells made from crystalline silicon). However, they also possess a low efficiency and have a low versatility for circuit design. Thus our research group at Center for High Technology Materials (CHTM) at the University of New Mexico has developed a new quantum-dot (QD) based, thin film, micro-chip photovoltaic approach utilizing the dots-in-a-well (DWELL) structure that has advantages in both the specific power and flexibility for DoD-based micro-autonomous systems. Due to the high dot density (1×10^{11} cm^{-2}) and the DWELL collection mechanism, the spectral response and conversion efficiency is improved for small solar cells. This result was previously explained by the realization that the DWELL structure limits lateral current movement and subsequent edge recombination. As a result, the DWELL cells are promising for concentration and flexible surface applications for which shrinking the size of the device and maintaining high charge collection efficiency are of paramount importance.

Finally, we have shown that the most near-term viable wing membrane would be composed of Kapton, yet the nylon nanopaper is also promising if the handling and processing issues can be overcome. An artist's conception of the micro-autonomous flyer is shown in the Fig. 8 with a summary of the MAST performance goals compared to existing amorphous silicon solar cell technology.

6. ACKNOWLEDGMENTS

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