Concurrent engineering in designing a system for sensing gas leaks in harsh space environment

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Abstract: *Leak monitoring is an essential operation that must be taken into consideration while making the design of a spatial vehicle. In order to make these vehicles function correctly in space and to avoid disasters, one needs to integrate multiple sensors to determine the exact concentrations of fuels such as hydrogen, hydrazine, hydrocarbon or oxygen which are frequently used while launching a space vehicle. These concentrations are important, as hydrogen-oxygen mixtures can ignite with a very small amount of energy. Moreover, it is almost impossible for people to sense the presence of hydrogen, as this gas is odorless and colorless. In the propulsion industry, hydrogen leaks generated several disasters. In 1990 such an error affected the propulsion system while workers were on the launching platform. They were forced to abort all the current processes until the source of leakage could be identified. Another example is the APOLLO 13 mission that took place in 1970 when N.A.S.A aimed to land on the Moon. Two days after the launch there has been a malfunction of the electrical system which caused an explosion leading to the loss of oxygen in both tanks. The crew used a module called lifeboat on their way back to Earth where they completed the landing. The goal of this paper is the describe the concept of an intelligent system that will monitor the presence of oxygen, hydrogen gas in harsh space environments such as vacuum, temperature variations and also beta and gamma radiations. Therefore, some aspects such as the weight of the device or environmental conditions must be taken into consideration when doing concurrent engineering. Micro and nanotechnologies allow the presence of multiple sensors without increasing the size, the weight or the energy consumption. Also, they must resist harsh conditions from space.*

Key Words: *hydrogen, oxygen, propulsion, concentrations, gas, energy, sensors, hydrocarbon, fuels, launching*

1. INTRODUCTION

In order to ensure safe travel through space, there have to be less unpredicted situations that cannot be fixed. Over time, gas leaks became a problem that must be taken into consideration since events such as the STS-35 mission must be avoided.

This paper aims to describe an intelligent system that will monitor the gases such as oxygen and hydrogen in conditions that involve vacuum, radiations or temperature variations. This article will present the basic theory applied to gas sensors, details on experiments that were performed, a brief characterization of the sensors and the results that were obtained. Monitoring gas leaks have been investigated using wireless sensors networks on terrestrial structures and spacecraft. For example, the authors in [1] surveyed general leak monitoring methods, analyzing challenges of the space environment, such as meteoroids and space debris impacts, charged particles radiation, temperature cycling, vacuum environment, etc. damaging sealed structures, and demonstrating that only a multi-sensor data fusion method allows diagnosing the leaks and the leakage rate thus allowing for rapid leak detection and location in sealed spacecraft structures. This method is validated by a ground experiment, confirming that the spacecraft sealed structure leak reason, location and leakage rate can be detected accurately and effectively.

Another method to real-time detect spacecraft damage and determine gas leaks accurately is by using an acoustic sensor array to detect the acoustic signal which is emitted from damaged areas of the spacecraft on orbit, calculating the difference of arrival and beamforming algorithm to locate the damage and leakage [2]. As such, the extent of the spacecraft damage is assessed according to the nonlinear ultrasonic method, locating the damage position, and identifying the damage degree effectively, while meeting the needs of structural damage detection for the spacecraft in-orbit.

In [3] gas leaks were monitored using infrared imaging detection by investigating the performances of an MDGC (minimum detectable gas concentration) model using an MDTD (minimum detectable temperature difference) model that is used within the thermal imaging systems. Gas temperature and the amount of gas are considered when analyzing the results provided by systems based on infrared thermal imaging. The study concluded that it is more efficient to directly calculate the MDGC applied on MDTD, a process that will be done without changing the infrared measurement system.

The article [4] aims to analyze the RELL (Robotic External Leak Locator) used to measure the level of gas leaks on ISS (International Space Station). This is made out of spectrometer called RGA (Residual Gas Analyzer) and a Cold Cathode Ion Gauge. RGA can identify a certain type of gas out of all that can be found in that specific environment. They made a project that was supposed to test both the RGA and the Ion Gauge in terms of sensitivity within space and to see the factors that will affect the possibility of localizing gas leaks on ISS. In the article [5] a method based on a time-space domain correlation was used in order to establish a connection between the sensor array and gas leaks. This solution provides a high accuracy information regarding the location of the problem and solves the problem concerning the continuous ultrasonic signals that occur when there is a gas leak.

The paper [6] studies the importance of the problem in the context of loss in control of pressure that might lead to instability. Furthermore, researchers from Libelium aimed to detect leaks that occur within systems based on cryogenic fuel. The paper is structured as follows: Section 1 describes the basic theory applied to gas sensors, Section 2 presents the theory behind gas sensors, Section 3 presents the experimental details, Section 4 illustrates the concept of concurrent engineering and Section 5 draws the conclusions.

2. THE THEORY BEHIND GAS SENSORS

2.1 Basic theory applied to gas sensors

To develop an intelligent system that will detect gas leaks we will consider the following aspects:

Implementation: the technology should be adapted as sizes change when talking about sending devices into space. Therefore, micro and nanotechnologies will allow the sensors to be sent into space.

Reliability: the credibility of data coming from the sensors and the ability of the system to face unpredictable situations.

Redundancy: Systems allow a high scalability level if they are easy to install, reliable and without extra weight.

Inclusion: Every component has to provide another information on the vehicle system. Therefore, when all of these components are connected, they can provide complete information on the vehicle system [7].

Over the past years, the scientist tried to use different kind of materials that will improve the properties of sensors. Therefore, the SiC technology gained more and more interest due to the bond of Si-C that can be organized in different sequences [8]. 4H polytype is often used as it provides a high level of suitability in the electronic field. Furthermore, sensors that are based on SiC technology offer an excellent tolerance regarding radiation as it also offers a high thermal conductivity.

SiC sensors can work at high-temperature levels and can be used in aerospace vehicle propulsion where gas leaks play an essential role. A MOS capacitor based on a SiC semiconductor can be used to get a system that will be able to cope with significant temperature variations ranging between -270°C and 600°C.

The environment is an important aspect that needs to be considered while designing a sensor as in space there can be both special chemical conditions and also highly corrosive ones. Therefore, it is required for the sensors to have high sensitivity, long-term stability and the ability to detect different gases at high-temperature levels.

By using a capacitor (MOS), it is provided a detection mechanism that involves the dissociation of H2 over a catalytic metal that will form a dipole layer which will act as an interface between the metal and the isolator.

Therefore, in order to be able to use the MOS capacitor as a gas sensor, there has to be a strict control of the metal-semiconductor interface allowing the sensor to work even when the temperature increases.

Both molecular oxygen and hydrogen gas sensor created by Libelium can be used within the Gases PRO Sensor Board and programmed through Waspmote.

It is a calibrated sensor, so it is expected to work at its maximum accuracy for about six months. The molecular oxygen sensor has a sensitivity that ranges between 1.66 ± 0.238 nA/ppm and a temperature that varies between -20 ºC and 50 ºC. It can work correctly if the pressure ranges from 90 to 110 kPa. Its operating humidity ranges between 5 to 90% RH non-condensing, and it can respond in less than 30 seconds. In ideal conditions, it has accuracy as good as ± 0.1%.

The molecular hydrogen sensor has a nominal range that varies from 0 to 1000 ppm and a maximum overload of 2000 ppm. Its long-term output drift has a value which is smaller than 2% a signal/month, and it can respond in less than 70 seconds.

Moreover, it can work at a temperature that ranges from -20ºC to 50ºC and a pressure between 90 to 110 kPa.

2.2 Hydrogen sensing mechanism with MOS capacitor based on Silicon Carbide

The response of M/O/SiC capacitor to hydrogen-containing species is determined by electronic interactions at the interfaces of the structure. For a MOS structure, these interfaces are the ambient gas /metal interface, the metal/oxide interface and the oxide/semiconductor interface [9]. The oxide charges include four types of charges: trapped charge at the oxide-semiconductor interface, fixed oxide charge, oxide trapped charge, and mobile ionic charge. The last three types of charges, distributed inside the oxide, are positive and create a depletion region at the surface of the 4H-SiC semiconductor layer. This region modifies the flat band voltage of the MOS capacitor and produces a shift of the C-V characteristic. An adjustment of the electrical charge in the depletion region of the semiconductor occurs for any voltage applied on the gate metal [10]. Therefore, a decrease in band height is achieved in the silicon carbide. A larger gate bias voltage is required to drive the MOS capacitor from accumulation to inversion.

The mechanism enabling the hydrogen sensitivity of the devices based on silicon and silicon carbide semiconductors was described by Lundström et al. [11].

The chemical reactions that take place on the palladium surface, the hydrogen transport and the interface adsorption of atomic hydrogen for M/O/SiC capacitor are illustrated in Figure 1.

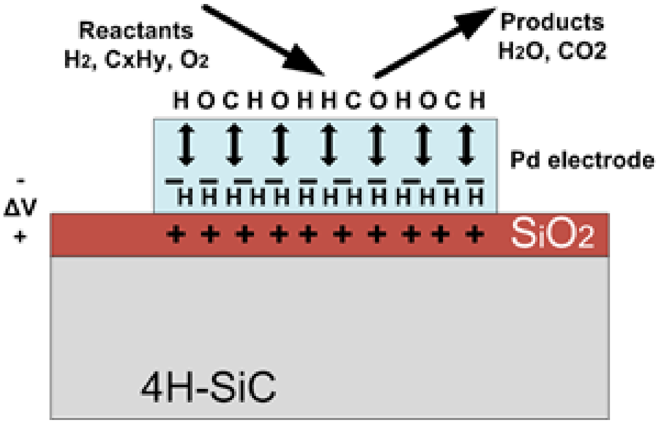


Fig. 1 - Hydrogen sensing mechanism for a MOS capacitor based on 4H-SiC

When the surface of the metallic thin film of the MOS capacitor is exposed to hydrogen gas, the molecules dissociate at the surface of the catalytic metal electrode and convert in hydrogen atoms. Some of the hydrogen atoms remain at the surface of the metal, and others diffuse into the metal until they reach the metal-oxide interface. There is an equilibrium between the number of hydrogen atoms adsorbed at the metal surface and the number of atoms adsorbed at the metal-oxide interface. The hydrogen atoms from the metal-oxide interface are polarized and create a bipolar layer. This bipolar layer decreases the semiconductor work function, which reduces the flat band voltage of the MOS capacitor. The change of the flat band voltage determines a shift of the C-V characteristic of the capacitor. The process is reversible, but not very stable [10].

The hydrogen response of the MOS capacitor has been derived from the Langmuir adsorption isotherm equations, which relates the voltage shift (ΔV) induced in the C-V characteristics of the gas concentration [11]. The kinetic equations for the transport of hydrogen in the metal electrode at equilibrium state are:

$$\frac{\mathrm{n_i}}{\mathrm{N_i}-\mathrm{n_i}} = k_s \frac{\mathrm{n_s}}{\mathrm{N_s}-\mathrm{n_s}}$$
$$\frac{\mathrm{n_s}}{\mathrm{N_s}-\mathrm{n_s}} = \left[\frac{\mathrm{c_1}}{\mathrm{d_1}}\mathrm{P(H_2)}\right]^{\frac{1}{2}} \tag{1}$$

where N_s and N_i are the number of adsorption sites at the metal surface and metal-oxide interface, respectively, n_s and n_i are the numbers of hydrogen atoms adsorbed at the metal surface and metal-oxide interface, respectively;
k_s and K (3) are constants that depend on the difference between the adsorption energy at the metal surface and the adsorption energy at the interface, c_1 and d_1 are constants of forwarding and backward reaction rate at the metal surface, and $P(H_2)$ is the hydrogen partial pressure.
The coverage of hydrogen at the metal surface (θ_s) and at the interface (θ_i) are:

$$\theta_s = \frac{n_s}{N_s}$$
$$\theta_i = \frac{n_i}{N_i} \tag{2}$$

The coverage of hydrogen at the metal-oxide interface can be expressed as a function of the hydrogen partial pressure:

$$\theta_i = \frac{\mathrm{K}[\mathrm{P(H_2)}]^{1/2}}{1+\mathrm{K}[\mathrm{P(H_2)}]^{1/2}} \tag{3}$$

The output signal of the MOS capacitor is the voltage shift (ΔV) induced in the C-V characteristic. The connection between θ_i and the voltage shift (ΔV) is obtained by assuming that the shift (ΔV) is proportional to the coverage of hydrogen atoms at the interfaces.
Where ΔVmax is the maximum shift of the C-V characteristic when the adsorption sites at the interface are fully saturated ($\theta_i = 1$). Finally, from Equations (1) - (3) the voltage change in the C-V characteristic can be expressed also as a function of the hydrogen partial pressure:

$$\Delta V = \Delta V \frac{K[P(H_2)]^{1/2}}{1+K[P(H_2)]^{1/2}}_{max} \tag{4}$$

3. EXPERIMENTAL DETAILS

3.1 Fabrication process

The (Pd/SiO2/SiC) capacitors were fabricated on an n-type 4H-SiC wafer, 0.015-0.028 x 10-2 ohm·m resistivity, with two epitaxial layers: a buffer layer with a thickness of 0.5 µm and the doped (ND=2.07x1016 cm-3) active layer with a thickness of 8 µm. Prior the sputtering depositions the 4H-SiC wafer was cleaned in two RCA solutions. For the organic contaminant's elimination, the solution was composed of ammonia, hydrogen peroxide and deionized water. For the ionic element's elimination, the solution was composed of hydrochloric acid, hydrogen peroxide and deionized water. The silicon oxide layer, with 30 nm thickness, was grown on the wafer by oxidizing at 1100oC for 2h in dry-O2.

The oxide thickness was determined by spectroscopic ellipsometry. The electrode (catalytic metal) of palladium thin film, with 50 nm thickness, was obtained by direct current

(DC) sputtering deposition, at 150 W in 5x10-3 torr Ar (99.999%) atmosphere. The circular dots with 300, 400 and 800 µm diameters were patterned using a micro-lithography mask and lift-off process. The equipment used for thin film depositions was UHV Sputtering& E-Beam ATC-2200V, AJA International Inc. USA. The ohmic contact on the back side of SiC substrate is made by DC sputtering an aluminum layer of 300 nm thickness.

3.2 Electrical response of Pd/SiO_2/SiC capacitor in the presence of hydrogen gas

3.2.1 Electrical measurement setup

For electrical characterization of Pd/SiO2/SiC capacitor of the smart system and the response to different H2 concentrations (from 0 ppm H2 to 5000 ppm H2) we developed in-house gas sensor test equipment, that is compatible with harsh environmental conditions from space.

The test equipment (fig. 2) is composed of: a gas mixing system with two mass flow controllers, a sealed chamber with oven and vacuum pump, a sensor biasing adapter, a signal conditioning system, a heater, power supplies and a digital LCR bridge. The function of mass flow controllers (MFC) for H2 and Ar is to attain precise concentrations of gas mixtures (from 0 ppm to 5000 ppm H2 in Ar).

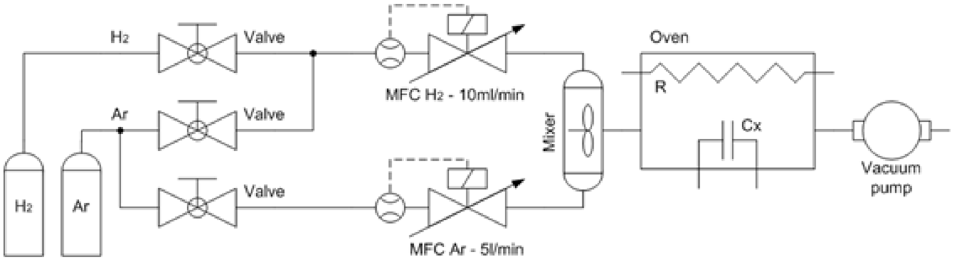


Fig. 2 - A schematic diagram of the measurement gas sensor equipment.

3.2.2 Experimental results and discussion

The response of Pd/SiO2/SiC sensors to hydrogen gas was characterized (Fig. 3) by measuring the capacitance of the sensor while exposed to various concentrations of hydrogen in argon gas (from 0 ppm - to 5000 ppm H2: Ar).

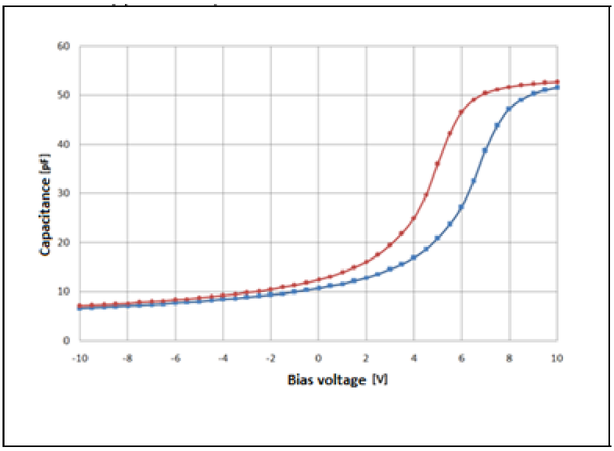


Fig. 3 - Electrical response of MOS device of H2 concentrations

It can be observed that the increase of hydrogen gas concentration creates a left displacement of the curve C-V towards negative voltages, on the bias voltage axis. A test on the influence of temperature on kinetic response was done by subjecting the sensor to a step signal (a sudden change in H2 concentration from 0 ppm to 5000 ppm H2: Ar), at 23°C and 200°C. The response (Figure 4) was significantly faster at higher temperature.

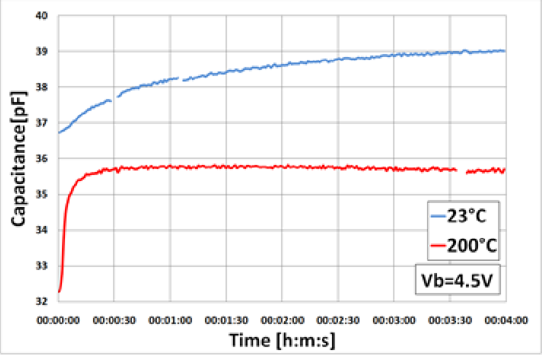
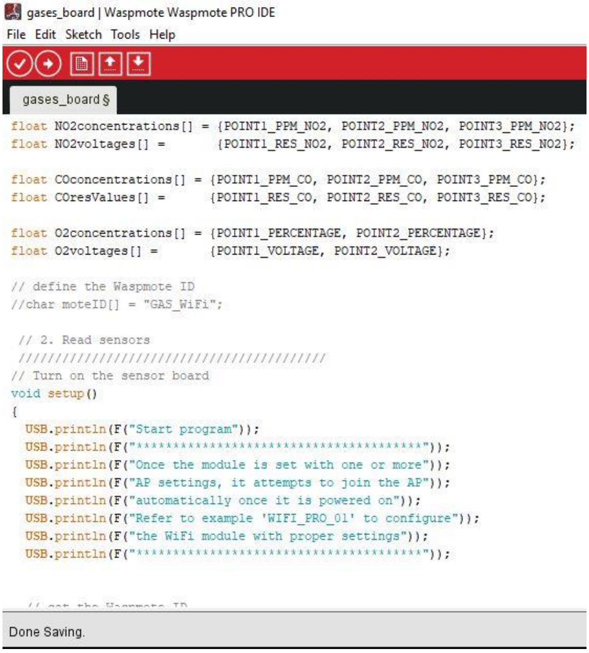


Fig. 4 - Sensor response to step signal (sudden concentration jump from 0 ppm to 5000 ppm)

If at 23°C the sensor response was not yet stable after almost 300 seconds, at 200°C, the sensor responded in less than 30 seconds, 10x faster. The measurement was done at a bias voltage of 4.5V. The goal here was to obtain the strongest signal possible and because the mass flow controllers take time to stabilize the flow of gas, a simple open/close manual valve was used. To validate the results, we used gas sensors connected to a Waspmote sensor network, which connect to the Internet and send data to a gateway router called Libelium Meshlium. Furthermore, we present how to connect a new Waspmote board to Meshlium device using the protocol called ZigBee. Nowadays, Grafana is considered to be one of the best open source platform allowing the user to visualize, understand the metrics, design and share with a certain team data collected from different sensors. Gas Pro Waspmote board from Libelium is used to measure the level of O2. The code that was used in order to read data from the sensors can be seen in Figure 5.



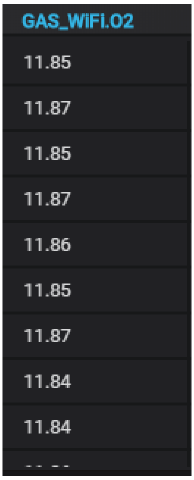
```
float NO2concentrations[] = {POINT1_PPM_NO2, POINT2_PPM_NO2, POINT3_PPM_NO2};
float NO2voltages[] =       {POINT1_RES_NO2, POINT2_RES_NO2, POINT3_RES_NO2};

float COconcentrations[] = {POINT1_PPM_CO, POINT2_PPM_CO, POINT3_PPM_CO};
float COresValues[] =      {POINT1_RES_CO, POINT2_RES_CO, POINT3_RES_CO};

float O2concentrations[] = {POINT1_PERCENTAGE, POINT2_PERCENTAGE};
float O2voltages[] =       {POINT1_VOLTAGE, POINT2_VOLTAGE};

// define the Waspmote ID
//char moteID[] = "GAS_WiFi";

 // 2. Read sensors
 ///////////////////////////////////////////
// Turn on the sensor board
void setup()
{
  USB.println(F("Start program"));
  USB.println(F("**************************************"));
  USB.println(F("Once the module is set with one or more"));
  USB.println(F("AP settings, it attempts to join the AP"));
  USB.println(F("automatically once it is powered on"));
  USB.println(F("Refer to example 'WIFI_PRO_01' to configure"));
  USB.println(F("the WiFi module with proper settings"));
  USB.println(F("**************************************"));
```

Done Saving.

Fig. 5 - Code used to measure the O2 concentration

Data can be displayed in Grafana and can be seen in Figures 6 and in Figure 7.

Fig. 6 - O2 concentration in Grafana



GAS_WiFi.O2
11.85
11.87
11.85
11.87
11.86
11.85
11.87
11.84
11.84

Fig. 7 - Data collected by Gas Pro

Moreover, a molecular hydrogen (H2) gas sensor was attached to the board. The advantages of this sensor are its capacity to operate at a temperature that varies from -20 ºC to 50 ºC and to stay in the air up to two years.

4. CONCURRENT ENGINEERING

The concept of concurrent engineering if frequently used nowadays as people want to perform multiple tasks in a shorter time. Solutions coming from a 3DExperience platform such as Enovia, Exalead, CATIA and Solidworks can help the engineer supervise the whole stages of a project [12]. Therefore, this platform allows the whole process to be integrated into a single environment during one life cycle of the product [13].

The radiation sensor board uses a Geiger-Muller tube that will measure the intensity of gamma and beta radiation level. Libelium used the radiation board to measure the level of radiation in space. They integrated a Geiger sensor and for this purpose, they were forced to reduce the size of the board.

Libelium made a collaboration with NanoSatisfi (the company that developed Ardusat). Ardusat integrated the Arduino technology within a satellite to enhance the access of researchers to this field of study. ArduSat aims to be an open source platform that allows scientist to develop their experiments and application in space.

They started from the board they used to measure the level of radiation after the Fukushima disaster and they used a Geiger counter sensor board on an Arduino. In space, this technology acts as a Geiger counter and will detect high levels of energy radiations. A 3D model of a Geiger tube was designed using CAD and it is displayed in Figure 8.

Fig. 8 - Geiger tube designed in CAD

5. CONCLUSIONS

The presented paper aims to highlight the importance of leak monitoring while making the design of a space vehicle that will integrate multiple sensors.

The H2 detection performance of the Pd (50nm)/SiO2 (30nm)/SiC sensor was analyzed at concentrations ranging from 0 ppm to 5000 ppm H2 in argon (Ar).

This shift of the C-V curve on the voltage axis is proportional with the hydrogen atoms adsorption by the metal layer and oxide layer and the changing of positive charges in the oxide layer and to the metal-oxide interface. Another possibility to operate the Pd(50nm)/SiO2(30nm)/SiC capacitor as a gas sensor is that the device is held at constant capacitance while modulating the gas concentration.

In this case, the bias voltage of the metal gate, required to maintain the capacitance, is the sensor signal.

The sensor response is more stable at high temperature. At 200°C, the sensor responded 10x faster than at room temperature. This certifies that the sensor based on silicon carbide is indicated for use in the harsh space environment.

The concept of an intelligent system was described regarding the sensors that were used and integrated using micro and nanotechnologies that will allow their presence without changing the size or the energy consumption. Furthermore, a brief description of concurrent engineering was provided to emphasize its importance within the development of a project in a company.

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