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MEMS HIGH-DOSES RADIATION SENSOR

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ABSTRACT

New MEMS sensor for detection of high doses (above 10 kGy) of radiation has been presented. The sensor is made of silicon and glass in a form of anodically bonded sandwich $9 \times 16 \times 2.6 \text{ mm}^3$. The sensor contains chamber with small portion of high density polyethylene (HDPE) and thin silicon membrane. Irradiation releases gaseous hydrogen, which flows from the chamber to the membrane. For known radiation dose pressure of hydrogen destroys the membrane, what is optically noticed. The sensor show good detectability of doses of radiation up to 120 kGy.

KEYWORDS

MEMS radiation sensor, high dose radiation, polyethylene degradation

INTRODUCTION

After Chernobyl/Fukushima affairs (Fig. 1) and other smaller accidents (Table 1), a need for relatively simple, cheap and easy-to-use sensors of high radiation doses became urgent, accompanied by the unsolved problem of measurements of high-dose levels inside new atomic reactors (nowadays 436 power reactors is operating in 30 countries (Fig. 2) and 62 are under construction [1]). The another problem here, is the post-process storage of nuclear wastes and reliable controlling of potential geologically or environmentally induced leakages.

Table 1: The main nuclear power station accidents where in International Nuclear Event Scale (INES) 4 is accident with local consequences, 5 is accident with wider consequences, 6 is serious accident and 7 is major accident [1]

Year	Incident	INES level	Country
2011	Fukushima	5/7	Japan
2006	Fleurus	4/7	Belgium
1999	Tokaimura	4/7	Japan
1993	Tomsk	4/7	Russia
1986	Chernobyl	7/7	Ukraine (USSR)
1980	Saint Laurent des Eaux	4/7	France
1979	Three Mile Island	5/7	US
1977	Jaslovské Bohunice	4/7	Czechoslovakia
1957	Kyshtym	6/7	Russia
1957	Windscale Pile	5/7	UK
1952	Chalk River	5/7	Canada



Figure 1: Accidents in Chernobyl (at left) and Fukushima (at right) nuclear power plants [1]

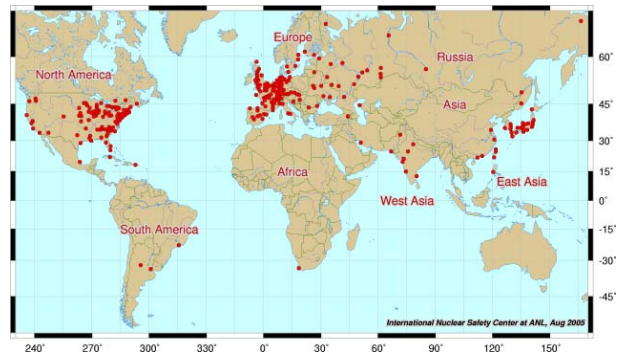


Figure 2: Nuclear plants in the world [1]

According to the today's state of art, high-doses of radiation (above 10 kGy) may be estimated *post factum* by family of passive thermo-, radio- and photoluminescence indicators or hydrogen pressure dosimeters [2, 3] but *in situ* measurements have been up-to-date obtained only for low or medium doses (below 10 kGy) by solid-state MOS based sensors [4]. So, the problem of high-dose radiation measurements is still open and important.

In the paper, MEMS sensor for measurements of high-doses of radiation, ranging from 10 kGy to 120 kGy has been shown for the first time ever. The sensor utilizes well known phenomenon (discovered in 50-ties of XX century) of degradation of polymers, e.g. polyethylene, polypropylene or polymethyl methacrylate [5], exposed to ionizing radiation (gamma, X-ray, electron beam, etc.).

CONSTRUCTION

A single sensor cell consists of the hermetically vacuum sealed container with a small portion of HDPE placed inside and the chamber with thin silicon membrane (Fig. 3a). Under the influence of ionizing radiation HDPE structure degrades releasing much of atomic hydrogen. Hydrogen flows from the container to the chamber through a channel and deflects the membrane. There are two modes of operation of the sensor available:

- "proportional", in which deflection of membrane is proportional to hydrogen pressure, thus to radiation dose;

- “destructive”, in which the membrane of known mechanical behavior is destroyed by overpressurizing.

The first mode is suitable for remote microwave readout system [6]. The second one seems to be useful for fast readout detection of a dose, especially if a sensor is built in a form of “cascade” of membranes of different planar sizes (Fig. 3b).

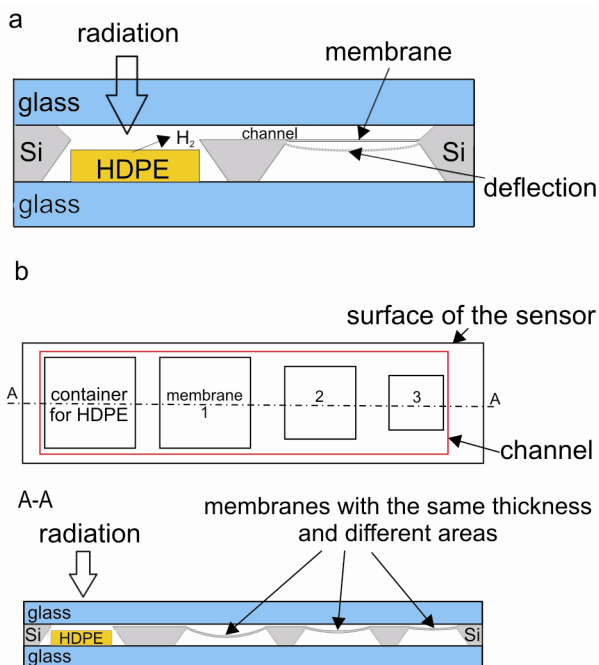


Figure 3: Schematic construction and work of a MEMS sensor of high radiation doses: (a) single sensor cell, (b) sensor with a “cascade” of membranes

FABRICATION

The sensor has been fabricated in MEMS technology, its overall dimensions are $9 \times 16 \times 2.6 \text{ mm}^3$. As mentioned earlier, each sensor contains sealed chamber - a container for small portion of HDPE. Hydrogen – being result of its degradation – flows through the microchannel toward moveable thin silicon membrane, causing its deflection or destruction. Each sensor consist of three layers: a monocrystalline silicon wet deeply etching micromechanical body and two glass covers (Borosilicate 3.3., Schott, Germany) anodically bonded. Fabrication procedure (Fig. 4) includes oxidization, photolithography and double-side KOH selective etching (80°C , 10M KOH, oxide mask) of double-side polished (100) n-type, silicon wafer (ITME, Poland). Such process forms the sensor body with via hole for the HDPE container, flow-channel and membrane(s). Following this, first anodic bonding of back side glass cover to the processed body is made in air at 450°C , 1000 V. After that, a pre-form of sensor (body/cover) is placed onto the heated table of anodic bonding machine, small portion (3.5 mg) of HDPE is precisely placed inside the container and anodic bonding of top side glass cover is done in pure nitrogen, under atmospheric pressure, in approximately 300°C , for 1200 V.

Two methods of inserting of HDPE have been tested: pipetting of drops of organic solution of HDPE followed

by 10 minutes bake-up in 100°C or direct placing of solid pill-like HDPE samples. First method gives potential of automatization of the procedure, but several problems with proper anodic bonding have been noticed, caused by unwanted contamination of the bonded surfaces. The second method appears to be very suitable on the laboratorial step of experiments.

After bonding, samples are cooled down to an ambient temperature. No temperature degradation of HDPE has been noticed.

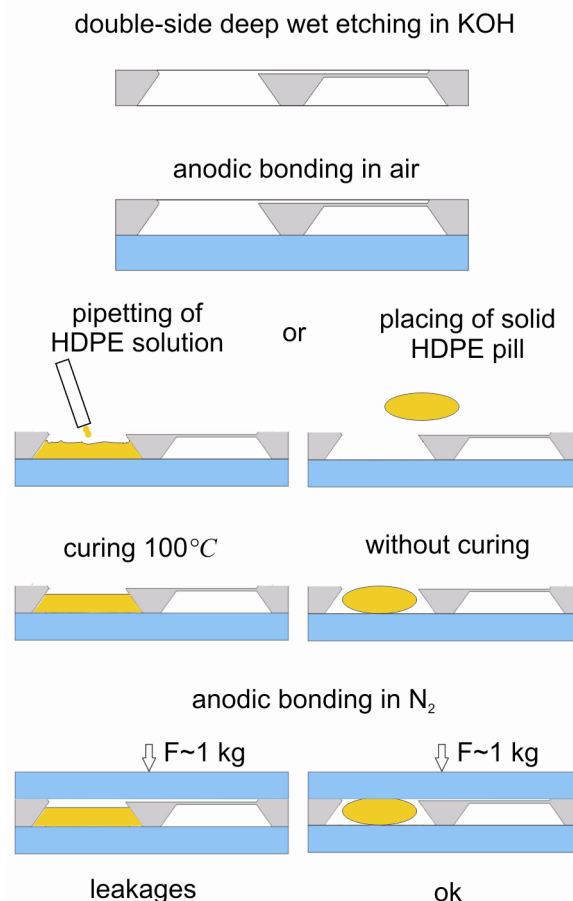


Figure 4: Fabrication process (single unit)

Several sensors with different membrane sizes and thicknesses have been manufactured (Table 2).

Table 2: Examples of manufactured membranes in sensors

single sensor			
membrane		thickness	
[mm ²]		[μm]	
5 × 5		15	
5 × 5		20	
5 × 5		30	
“cascade” sensor			
membrane	membrane	membrane	thickness
[mm ²]	[mm ²]	[mm ²]	[μm]
5 × 5	4 × 4	3 × 3	15
5 × 5	4 × 4	3 × 3	20
5 × 5	4 × 4	3 × 3	30

Simulations (Comsol Multiphysics MEMS Module) show (Fig. 5) that higher doses, above 70 kGy, need wider, thicker membranes and lower, below 70 kGy, should be thinner.

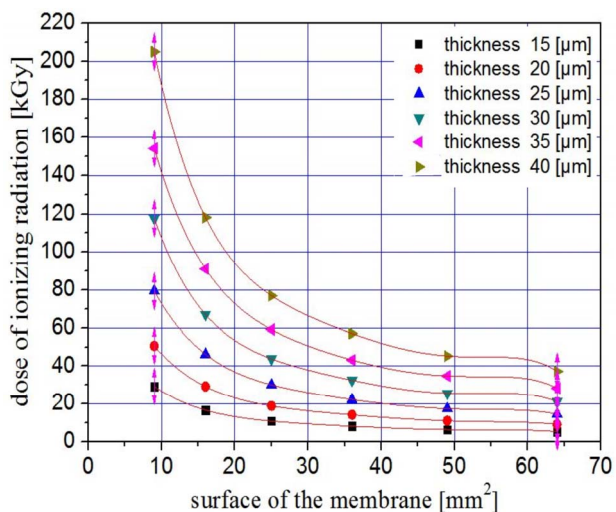


Figure 5: Dose of ionizing radiation needed to blow-up membranes with varying surfaces area and thickness - results of modeling

EXPERIMENT

Sensors have been tested in the test bench (National Centre for Nuclear Research, Otwock, Poland) consisting of linear accelerator equipped with removable conversion plate (Fig. 6). Prior to measurements the test bench has been calibrated with the Farmer Ionization Chamber method. During measurements sensors are placed inside a special chuck-holder to ensure repeatability of irradiations. Samples have been irradiated by high energy electron (6 MeV) and X-ray (4 MV) beams (Fig. 7). Pulsed electron beam of 3 mm spot size irradiates HDPE container only. X-ray beam irradiates the whole sensor. Dose of radiation is adjusted by electron/X-ray beams pulse length and pulse repetition rate change. Usually, irradiation of sensors by electron beam have been at least 10 time more effective in comparison to X-ray. Irradiation dose has been ranged from 10 kGy to 120 kGy.

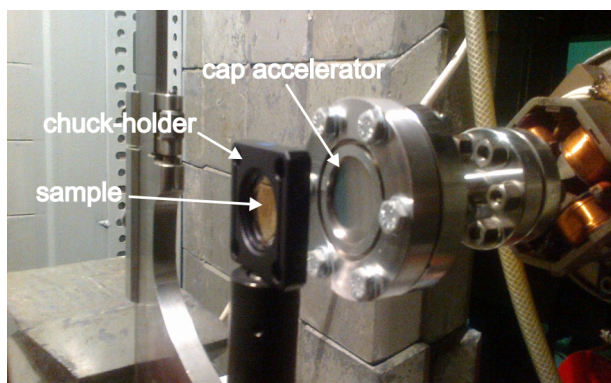


Figure 6: Experimental measurement set-up

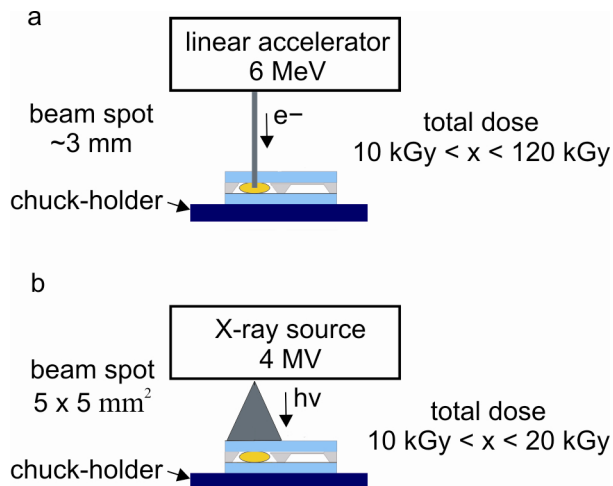


Figure 7: Methods of irradiation: (a) high energy electron beam; (b) X-ray beam

Tests have confirmed that, the sensor may work in two basic methods: deflection or destruction of membrane proportional to doses (Fig. 8).

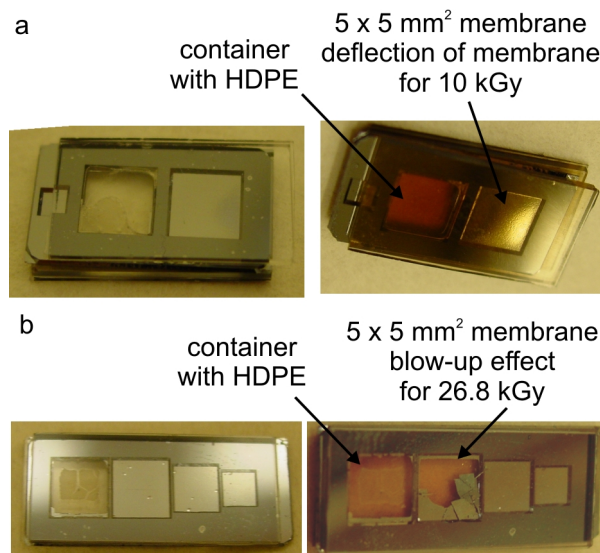


Figure 8: Testing of sensors: (a) single unit sensor before (left) and after (right) irradiation, dose 10 kGy; (b) sensor with "cascade" membranes before (left) and after (right) irradiation, dose 26.8 kGy. Results obtained for 30 μm-thick membranes

Tests show that presented here sensors may be used successfully for detection of radiation doses in the destructive mode at least for a range of 10-120 kGy (Fig. 9).

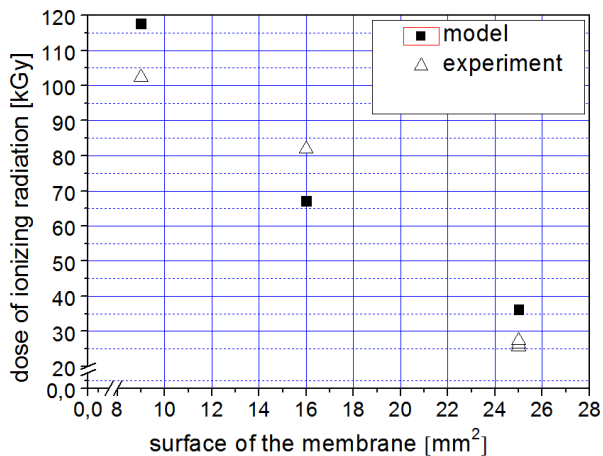


Figure 9: Sensors characterization: destructive dose of irradiation as a function of surface of 30 μm -thick membranes

In experiments we noticed significant influence of high doses of radiation on optical parameters of Pyrex-like glasses (Fig. 10). Hoya SD-2 shows significant changes, becoming brown for 10 kGy doses. Much smaller optical degradation is observed for Corning 7740, and the best stability shows Borofloat 3.3.

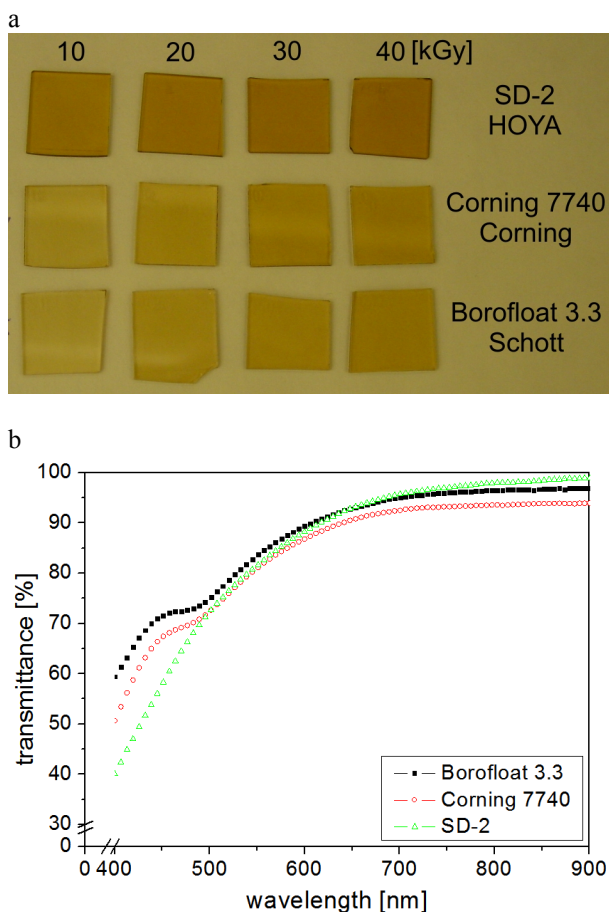


Figure 10: Degradation of Pyrex-like glasses irradiated by high-dose radiation: (a) sample of glass after irradiation; (b) transmission spectra curves of irradiated glass at 10 kGy dose

SUMMARY

MEMS miniature sensor for detection of high doses of ionizing radiation (10-120 kGy) has been fabricated and tested.

In the sensor small portion of HDPE is hermetically sealed inside sandwich of glass-silicon-glass structure with a set of precisely etched, thin (15-30 μm) square membranes (25, 16, 9 mm^2).

Irradiated HDPE degrades, realizing gases hydrogen, which pressure is proportional to a dose of radiation. Hydrogen pressure deflects and furthermore destroys step-by-step each of membrane (widest first). Test have shown that sensor successfully detected 25 – 81 – 102 kGy doses.

At the actual development stage several negatives have been noticed anyway, including degradation of Pyrex-like glasses and their bondability. There are several questions concerning linearity and reliability of our MEMS sensor, scaling and degradation of structures of materials under strong irradiation (especially important for borosilicate glasses). Precise measurements of volume of hydrogen released from HDPE must be done as well. Anyway, the presented here results open the way toward family of wireless micro-sensors of high radiation.

The sensor is a very good demonstrator how the pretty old principle “dressed” in a new microengineering formula gives, potentially attractive solution in a microscale.

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