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Semiconductor Strain Gages Applied to Examined Objects Development, Production and Their Application during the Period between the 1st and 50th Conference EAN

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Abstract: Rules for preparing a paper for proceedings of the conference EAN 2012 are provided. After the basic requirements specific guidelines are given for all major elements of the paper (such as abstract, keywords, headings, figures, tables, equations, and references). The use of complete and properly formatted references is particularly important.

Keywords: Experimental; Stress; Analysis

1. Preface

Discovering semiconductor piezoresistive effect, American physician C.S. Smith [1] extended the range of strain gage application. The transmission of deformation to electrical signal was by 1,5 order higher in comparison to metal strain gages, contemporarily with higher sensitivity threshold = 8.10^{-10}, when the active signal is 10 times higher than noise and which make possible to indicate relative deformation quite several thousands of millimeter on the base of 1 km. In the beginning semiconductor strain gages were made of easy processed germanium, later of silicium. Its resistence response to deformation shows moreover no measurable plastic signal up to 400 deg of Celcius. As the thermal expansion coefficient of silicium iss 6.10^{-10} /^{0}C , what is only a part of the same quantity of metals and if we apply them on metal parts by means of suitable adhesives and cured them under higher temperature, semiconductor strain gages are preloaded in pressure. On steel this value is – 1.10^{-3}, on aluminium alloys – 2.10^{-3}. Semiconductor strain gages generally show higher resistance to dynamic loading than foil strain gages made of alloys Cu55Ni45. The silicium, loaded in the range of fatigue limit, does not change its resistance value as it is seen at alloys used for foil strain gages and if brakes the resistance value increases minimally hundred times. High fatigue life time of silicium strain gages together with high deformation sensitivity make possible to design strain gage transducers with warranty higher than 1.10^9 cycles. Semiconductor strain gages are substantially more expensive than metal ones due to the price of raw material and processing and as every strain gage is tested in the range $\pm$2,5. 10^{-3} in steps – 5.10^{-4} . From this loading test the customer receives protocol containing all characteristics.

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First semiconductor strain gages, made of germanium, were launched to market in 1957, first silicon ones in 1959. The time gap between discovering and industrial manufacturing was due to their manufacturing complexity. The technology of the year 1954 allows to produce silicium electronic parts, having thickness several hundredths millimeter, but their limit strength deformation did not exceed the limit + 1.10^{-3} . Those strain gages were applied very limited for strain analysis.

2. The development of production technology for silicium strain gages in Czechoslovakia

The reason for development of semiconductor strain gages was at the first the embargo of modern technologies and products for the countries of the Soviet bloc, that was existing up to the seventieth. In Czechoslovakia there were several (minimally six) work-places developing silicium strain gages or membranes with diffused strain gages. Moreover the raw materials and their prices were very suitable (about 3 Czech crowns per one pieces) and the efficiency of development and production very high (price of one silicium strain gage was about 20 US dollar for home customer as well as for foreign one). Main workplaces and researchers dealing with semiconductor materials for application in stress analysis are listed here:

a) State Research Institute for Machine Construction **(SVÚSS)** in Běchovice, where research was headed by **Ludvík KUHN (1925-1991)**, the author of the first Czech publication on piezorezistive effect in semiconductors and its application in control technique [2]. Dr Kuhn was continuing in development of germanium strain gages and developed technology of semiconducting membranes for pressure transducers;

b) Institute for Thermomechanics of the Czechoslovak Academy of Sciences **(ÚT ČSAV)** in Praha, where **Ladislav TOMANEC (1928-1977)** developed technology of silicium sensors with diffused strain gages;

c) Research and Testing Institute for Aeronautics (**VZLÚ)** in Letňany /Prague, where **Ivan Řezníček (1927)** [3] was dealing with problems of production, application and exploitation of semiconductors for aircraft application as well as for general purpose. His colleagues were **Ladislav HRUBANT (1934), Karel KOZÁK (1935)** and **Jiří LUKAS (1938-1997).**

In 1964 to avoid duplicities in research, it was decided to exchange all information dealing the above mentioned problems among all involved workplaces and about the reached state. If any workplace had better results, this would have right for follow-up. This gentleman agreement was fully used between VZLÚ and SVÚSS, when L. Kuhn gave a chance to I. Řezníček to start technology development in VZLÚ by giving one Si-monocrystal having extreme low specific resistance, which was in short supply in Czechoslovakia at that time.

In the above mentioned collaboration there is missing company TESLA Rožnov as a company with military production, which had good instrumentation for producing silicium sensors with diffused strain gages. The collaboration started much more later with the help of **Karel POSPÍŠIL –** Research Institute for Communications A.S. Popov in Prague.

In 1967 the division of labor was done according to results in each single workplaces. SVÚSS worked out sensors with diffused silicium strain gages, ÚT ČSAV was developing generally applicable types of silicium membranes and VZLÚ was developing technology for producing silicium strain gages applied for stress analysis.

The conditions for developing new products were not simple in so called "socialist economy". For products having mark of high quality as silicium strain gages are, it was necessary built up conditions in form of "clean" new rooms and testing machines. A part of testing machines was bought from abroad, the rest was produced in VZLÚ according to the American Code NAS 942. This was in hands of the head of the Measuring Technique Department **Jiří ČERNOHORSKÝ (1930).**

At the end of 1968 the principal operation, covered by five patents of invention, for producing silicium strain gages were fully managed and mastered, particularly:

- connecting gold outlets to silicon strips by means of own original way, that ensured better connection than thermo compression technology;
- reducing the thickness by means of chemical machining instead of grinding.

Technical solution was sometimes influenced by political circumstances. In 1968 the occupation of Czechoslovakia by Soviet army brought very unfortunate consequences. In November 1968 I. ŘEZNÍČEK left Czechoslovakia for Switzerland. Later he with his colleague founded company REZNICEK & HLACH AG there, that was developing and producing broad spectrum of silicium strain gages and special transducers on strain gage principal of all possible kinds. After I. Řeznícek´s departure, his group in VZLÚ was divided in two ones – the developing of metal strain gages was headed by J. LUKAS and development of silicium strain gages by L. HRUBAT.

In 1979 the improvement of chemical machining increased limit tensile deformation up to + 6.10^{-3}, but for most applications (approx. 60%) the maximum elongation + $2{,}5.10^{-3}$ is enough. During all operation keeping of working regulation ensured high quality of products. In spite of this fact sometimes the regulations are not kept and then there is no possbility only to throw out spoiled products.

Nonomiting part for successful application of strain gages are adhesives. Silicium strain gages need adhesives of higher quality than for metal ones. The reason for this demand is in higher thickness of active part (approx. 18 micrometers) and consequently higher stiffness in comparison with metal strain gages. The criterion of the adhesive quality is slippage caused by adhesive creep and is given by the percentage decrease of strain gage signal from half bridge configuration under loading defined by deformation + 1.10^{-3} and thermal and time conditions (24 hours, 25^{o} C). Ordinary structural adhesive have slip 2 % - 10 % of the defined signal.

The adhesive for silicium strain gages was developed on the base of epoxy resin having maximal slip 0,1 % for temperature range -60^{o} C $+60^{o}$ C by pair of employees of the Research Institute of Painting Coats **(VÚNH)** in Praha **Vladislav MERTL (1921)** and **Stanislav POKORNÝ (1923-2006).** This adhesive, having mark PT-5, was also delivered to Poland where pressure transducers were produced

in licence. For measuring on structures as well for material strength test and strain gage calibration, cyanoacrylat adhesive are adequate.

3. Silicium Strain Gage Production

Production of semiconductor strain gages started in the Research and Testing Institute for Aeronautics (VZLÚ) in 1970, only in laboratory measure with the year volume 1000 pieces. One year later the production increased to the number 3000 pieces. The most extensive application was presumed for weighing application as it had been prepared included testing procedures according to the requirements of the enterprice TRANSPORTA by I. Řezníček as early as in 1967. Together with the change of management (J. Černohorský left VZLÚ for enterprise INOVA, producing dynamic testing and loading machines) the new department head **Zdeněk MICHVOK (1935)** directed the semiconductors for application to flying aeronautical tests, particularly of the aircraft L-159.

In September 1972 bilateral negotiations between Czechoslovakia and German Democratic Republic (GDR) about orientation and specialization in the branch of measuring technique were realized. The Czech enterprise **RUKOV,** where the production as well as development was shifted from VZLÚ, offered delivering 1000 pieces of semiconductor strain gages till the end of year 1972, with possible increasing to 10000 pieces in 1973 and to 20000 in 1974. It is necessary to mention here two names **Oldřich STRAKA (1925-2003)** from company **RUKOV** and again **Jiří ČERNOHORSKÝ** now from company **INOVA** and one company - **Research Institute for Automation Devices (VÚAP) Praha.** The technology having been developed in VZLÚ was offered to RUKOV, but it refused this offer and was using its own technology. Thus all works round semiconductor strain gages was stopped in VZLÚ.

Simultaneously GDR representatives made an effort to gain technology from VZLÚ. If they were not successful they started production according to their own technology. But in competition with Czechoslovak products their products were weaker in quality (e.g. it was not possible to apply them to the radius lower than 3 mm). After several years of production, it was stopped at the end of seventies.

Similarly as in GDR company RUKOV had some problems with the semiconductor strain gages quality and that was why the limited production in VZLÚ was opened again. These products fully complied to at that time valid regulations of the company PHILIPS.

In 1973 opportunity jumped up to deliver our semiconductor strain gages to the Polish company MERA for pressure and force transducers produced on the base of licence from German company ASCANIA. It presumed to use American semiconductor strain gages, but it was fergotten they were as strategic goods under strict embargo. From three offered products (from Soviet Union, GDR and Czechoslovakia) the quality requirements proved Czech products. And up to the end of 1973 1000 semiconductor strain gages for pressure transducers were delivered to Poland.

As company RUKOV did not improve the quality of its products and as needs for semiconductor strain gages was increasing in our country as well as in

other so called all socialist countries, the semiconductor strain gages technology was offered to several companies in our country producing measuring and control devices and transducers. All of them (MIKROTECHNA Holešovice, MIKROTECHNA Modřany and MESIT) refused as this new technology brought higher demands on technology discipline, but without increasing of finances either forcompamy as well for employees.

Total semiconductor strain gages deficit on the Czech market gave possibility to offer the technology to other interested companies. In March 1974 **Zdeněk KRČÁL (1928-1998)** from Research Institute for Leather Manufacturing in Gottwaldov, who needed special force transducer very urgently, came to VZLÚ. The workers of VZLÚ prepared suitable solution, but under condition that he might help to find a potentional semiconductor strain gages producer. In June he brought two gentlemen with from the management of the REPAIRING ORGANIZATION OF THE TOWN GOTTWALDOV (OPMG – Opravárenský podnik města Gottwaldov) producing and repairing everything from the cradle to the coffin – **Karel VLČEK (1919-1998)** and **Karel HLAVÁČEK (1922)**. But these gentlemen immediately knew advantages of these new products and in a short time they prepared rooms, include laboratories with digesters and instrumentation suitable for the manufacturing as it was necessary for semiconductor strain gages manufacturing. Transfer of technology and worker training was done in a short time thanks to Deputy Director VZLÚ **Jaromír SCHINDLER (1921-1979)**. Since October 1974 OPMG was already producing semiconductor strain gages in series. All semiconductor strain gages from OPMG were tested in the mother laboratory in VZLÚ. Up to the end of 1974 4000 pieces were produced under heading of **Jiří MICHÁLEK (1946).** Perfect organization and technology discipline was normal for management (some of older were trained in Bata schools and later factories), what was not usual at that time.

In 1978 OPNG with all 400 people was "reorganized" to SERVICE ORGANIZATION OF THE TOWN GOTTWALDOV (OPSG – Okresní podnik služeb města Gottwaldov) having more people and more understanding for increasing demands in semiconductor strain gages production. The group producing semiconductor strain gages received further rooms and better instrumentation, shortly better conditions for producing as well as for life. The export to Poland was also increasing as the company MERA enlarged spectrum of its products and needed more semiconductor strain gages. The need at Prague mother workplace for semiconductor strain gages was also increasing (stress analysis on turboengine parts) and thus nearly 40000 semiconductor strain gages were produced in OPSG in 1979.

In 1978 OPSG expanded the service for clients by applying semiconductor strain gages to their elastic members by means of glue PT-5, by connecting inner electrical circuits and by compensating thermal shifting of zero point.Thus high quality of transducers was achieved (cumulative error = hysteresis + nonlinearity was 0,2% - 0,5% according to sensor type, overloading 200% and lifetime more than 10^8 cycles). Under the heading of **Ivan HEJTMÁNEK (1948)** and later **Petr KATAUER (1968)** 100 transducers were produced only in 1978 and in 1989 1200. Foreign companies started with producing similar transducers later (HBM in 1979).

At the beginning 1991 after political changes in our country, five gentlemen (J. Michálek, I. Hejtmánek and P. Katauer from Zlín together with L. Hrubant and K. Kozák from Pargue) founded manufacturing corporation **VÝROBA TENZOMETRŮ A SNÍMAČŮ (VTSZ)- STRAIN GAGE AND TRANSDUCER MANUFACTURING ZLIN**. After privatization it purchased relevant part of the Service organization and three years later they moved to its own building. Some members left the corporation due to age or health and now only Petr KATTAUER remains and is heading poduction of strain gages and transducers, occasionally with the author´s help.

4. Examples of silicon strain gages developed or produced in Research and Testing Aeronautical Institute (VZLÚ)

4.1. Transducers of mechanical quabtities

Semiconductor strain gages developed bd produced in Czechoslovakia and later in Czechien were applied in 70000 pieces of pressure transducer for industrial automation in Polish factories MERA-ZAP, Ostrów Wielkopolski and MERA-PNEFAL, Warszawa–Falenice. The accuracy class with the relevant electronics was 0,5%. At the beginning the customers from the Soviet block did not have confidence in this data and carried out their own calibration. For example in 1987, one Est-german client was checking 360 pressure transducers and the Hungarian one 280 pieces. None from this total amount proved worse accuracy than the guaranteed limit. If only one transducer had its accuracy worse, the total delivery quota would have been sent back according to the delivery contract. In 1994 the above mentioned producers started to produce pressure transducers for industrial automation equipped with silicium membranes having diffused strain gages.

In Czechoslovakia and later in Czechien one could meet further quality increase at transducers equipped by semiconductors strain gages prepared in OPSG, granting the accuracy of the transducer by one order higher. Some illustrative cases are attached:

1979 –PAL - MAGNETON Kroměříž, producing strain gage corrector of the flying altitude and slip gage of the gyropilot for the aircrafts L- 410. Both instruments were and still are fully comparable with instruments of the American company Bendix.

1980 – TESLA - Valašské Meziříčí, in relative big series producing gages for checking the childbirth course, allowing determining coming birth and avoiding danger for the child following from oxygen deficiency.

1984 – MOTEX – Praha Strašnice, producing gages for measuring braking forces and force gages acting on the braking pedal. Both were and are used for braking test of motor-cars in laboratories over all our country as well as at out neighbours.

1986 – AGROZET - Přelouč, producing balances up to 500 kg, used in technology agriculture lines.

In OPSG Zlín some single purpose challenging transducers and gages were realized:

1985 – in collaboration with VZLÚ gages for determining total mass and centre of gravity of the aircraft IL-62M, having maximum take off mass 160 tons. The measuring units were carrying parts of the undercarriage having mass of 120 kg and length 2000mm. Under supervision of the Czechoslovak Airlines workers (the temperature by adhesive hardening was not allowed to exceed 210^{o}C) these parts were equipped by semiconductor strain gages.

1986 – in collaboration with Research Institute for motorcars (ÚVMV) Praha and VZLÚ the measuring wheel M-01, allowing precise measuring way for simulation of driving conditions on the cylindrical dynamometer in laboratories. This device was awarded by the Golden Medal at the Prague exhibition AUTOPROGRESS´86 and was exported to German Democratic Republic, Poland and Soviet Union.

Between 1991 and 2011 a great set of single-purpose transducers and gages, serving for research and development in civil engineering, chemistry, medicine and agriculture, were designed and produced in VTS Zlín.

4.2. Experimentl Stress Analysis Extremaly Loaded Turboengine Parts

A slight mistrust to semiconductor strain gages application was surpassed, when in 1975 during vibration fatigue test of compresor blade for the new developed turboengine M-601 (producer company MOTORLET) for the Czechoslovak aircraft L-410, imported foil strain gages failed. This drop out in testing endangered prosperous finishing of its tests in time. The application of semiconductor strain gages from the company OPMG, prepared by **Jiří NOVÁK (1938-1979)**, meant the very hopeful solution of the determining stress state in loaded turbo-blades. Semiconductor strain gages proved successful operation during these and further tests. The practical experience opened broad field for many application either for aicraft problematis or for common usage.

During the period 1979 – 1990 semiconductor strain gages were applied for stress determinating in a wide set of points in the disc of generator´s turbine and in radial wheel of the compressor during operational condition (40000 rot per min and at teperature 250^{o} C). During these tests semiconductor sensor were also used for determing temperature field in the followed parts. After having finished these tests, some strain geges were tested, if they did not change their characteristics during operation. This additional test was done on comparison of the temperature characteristics before and after tests. This possibility to check correctness of the stress analysis during long term test was further great advantage of semiconductor strain gages.

After Jiří NOVÁK´s leaving **Jindřich HURYCH (1930-1982)** finished the tests of turboengine M-601. High accuracy of the results in semiconductor application required beside perfect instalation of strain gages also reliable signal transef in the whole measuring chain and sofistic processing measured values. **Jaroslav DUFEK (1925)** improved the measuring methodology using statistical processing measure data. And thus the achieved cumulative error at measuring on rotating parts was in the range $\pm$2% - $\pm$4%. This approach of processing measured data has been used up today.

5. Conclusion

In 1974, starting production of semiconductor strain gages in OPMG Zlín, having all marks of high quality, ranked Czechoslovakia to the fifth place in the whole world family of countries, producing this sort of strain gages. Progress in electronics during further years partially decreased significance of high deformation sensitivity of silicium and caused lower number of application in areas, where high sensitivity was necessary.

Silicium semiconductor strain gages need also higher demands to technical level of applicants in comparison with foil resistance strain gages. But specific qualities of semicoductor sensors make possible to reach more accurate and reliable result in comparison with metal strain gages in many ranges of experimental stress analysis.

Scopes, given to similar overview as this presentation is, gives only limited possibilities to mention only milestones on the way from the beginning to the present state. The author apologize for omitting all others who has helped to semiconductor strain gages on this 50 years long way or who have taken part in their application. For their work and contribution the author expresses cordial thanks to them.

References

[1] Smith. C.S.: Piezorezistence Effect in Germanium and Silicon, *Physical Review*, 94, 42-49, 1954.

[2] Kuhn, L: Piezorezistence Effect in Semiconductors and Its Application in Measuring Technique (in Czech: Piezorezistentní jev v polovodičích a jeho aplikace v měřící technice), int. report SVÚTT 63-07 008, SVÚTT Praha, Dec 1963.

[3] Řezníček I.: About Some Qualities of Semiconductor Strain Gages (in Czech: O některých vlastnostech polovodičových tenzometrů), seminar and scriptum Pokroky tenzometrických metod ve strojírenství, 11.4.1968 Dům techniky ČSVTS Praha).

[4] Hrubant, L., Kozák K.: Application of Czechslovak Silicon Strain Gages for Stress Analysis of Turboengine Parts (in Czech: Vyžití čs. křemíkových odporových tenzometrů k měření namáhání částí turbovrtulového motoru), *Proc 20th Conference EAN ´82*, 31.5.-3.6.1982, Karlovy Vary.

[5] Hrubant, L., Kozák K.: Mass Determination of the Aircraft IL-62 M by Means of Semiconductor Strain Gages Picking Stress State in Undercarriage Parts (in Czech: Měření hmotnosti letadla IL-62 M polovodičovými tenzometry, snímajícími napjatost částí podvozku), *Proc 24th Conference EAN´82*, 27.5.-29.5.1986, Olomouc.

[6] Minutes and protocols from talks and meetings and correspondence between 1962 – 2012.