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HARD QUASIAMORPHOUS CARBON - A PROSPECTIVE CONSTRUCTION MATERIAL FOR MICRO-ELECTRO-MECHANICAL SYSTEMS

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ABSTRACT

A new form of sp^3/sp^2 carbon has been fabricated which exhibits a large number of valuable properties. This material combines low density ($\leq 1.65 \text{ g/cm}^3$), low stress ($\leq 0.05 \text{ GPa}$), low thermal expansion ($1.6 \times 10^{-6} \text{ K}^{-1}$) with high hardness ($\sim 30 \text{ GPa}$), modulus ($\sim 200 \text{ GPa}$), cracking threshold ($\geq 3 \text{ N}$), fracture toughness ($\geq 10 \text{ MPa-m}^{1/2}$), long-term thermal stability ($\geq 450^\circ\text{C}$ in air and $\geq 600^\circ\text{C}$ without oxygen), extremely high thermal shock resistance, excellent interface and adhesion to silicon, metals, and ceramics and an absolute resistance to the silicon etching acids. Most of its properties are actually constant up to 700K . The material combines a basically amorphous structure with one-axis anisotropy and a graphite-like layered arrangement with a length scale of the modulation about $14\text{\AA}$. We refer to this quasi-amorphous material as QUASAM. This paper describes QUASAM synthesis conditions, growth front planarity and material characterization with high-resolution x-ray diffraction, positron annihilation spectroscopy, atomic force microscopy and micro-Raman spectroscopy. In addition the mechanical and thermal examination of QUASAM and QUASAM/Si will be presented in terms of micro-electro-mechanical systems (MEMS) and the technology prospective requirements of MEMS.

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MASTER

MEMS are the most integrated devices which together operate electronics, mechanics, and numerous phenomena of the solid - milieu interaction. Having been designed for diversified operational conditions, including extreme temperature, pressure, acceleration and vibration, radiation, corrosive environment, and even internal function in human body, MEMS must contact directly with gases, liquids, or a solid contra-body. They may proceed some executive as well the control functions that restricts the device reservation and toughen the reliability requirements. On the other hand, MEMS technology is a symbiont of IC technology, it must be silicon-compatible, the maximum temperature of MEMS fabrication is limited, while MEMS themselves must be resistant in certain final operations of IC fabrication. In the past few years, MEMS industry exceeded the \$1-billion-a-year mark and may surpass \$14 billion by the year 2000 [1]. Such a giant mass-production and common use require the bio- and environmental compatibility of the basic MEMS material, and only carbon may strategically satisfy all these requirements.

This paper describes a new carbon form having been developed as a result of over decades search for a carbon-based material initially for the computer IC, and later [2,3,4] also for micro-electro-mechanics. This material was developed recently, the real MEMS weren't fabricated yet. But its properties and technology are characterized in terms of the current and potential MEMS requirements like the possibility to produce thick films which satisfy mechanical requirements, and a competitiveness with polysilicon films [5], planarity and the technology potential for cross-

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sectional design [6], the requirements for a "portable process" [7]. Some more severe conditions have been also applied to test the free-standing QUASAM and Si/QUASAM heterostructures.

EXPERIMENTAL DETAILS

Synthesis

The material was synthesized by vacuum deposition from the predominantly low-molecular radical ions like CH^{*+} , SiO^{*+} in rf (1.76 MHz) accelerated field. The most critical deposition parameters are substrate temperature and impact radical energy which is defined with accelerating voltage. The QUASAM material is synthesized in synergetic conditions of a combined thermal and impact activation of the growth reactions [8] at the substrate temperature range 500 K - 700 K, and accelerating voltage in the range of 20-200 V. The films were successfully grown in accelerating field of different frequency (100 kHz - 13.56 MHz and dc), however all the following results correspond to rf field 1.76 MHz. At the higher accelerated voltage and low temperature a diamond-like atomic-scale composite (DLN) [9]) is forming, while a graphite-like material grows in the higher temperature range. The radical beam was generated by a multi-cascade remote plasmatron using high-boiling silicon-organic precursor polymethylphenyldisiloxane similar to DLN synthesis [9]. However an essentially more powerful regime of plasma generation was used to synthesize QUASAM resulting with beam density $w \approx 4 \times 10^{16}$ radical/cm² s while in DLN technology the typical beam density is about $w \approx 1 \times 10^{15} - 2 \times 10^{15}$ radical/cm² s. The typical growth rate of QUASAM was in the range 15 $\mu\text{m/h}$ - 20 $\mu\text{m/h}$ (over 30 $\mu\text{m/h}$ was achieved in some experiments) while the DLN growth rate is in the range 0.2 - 2.0 $\mu\text{m/h}$. The plasma discharge is generated in crossed D.C. (radial) and r.f. (axial) electrical fields with W-Th hot filament. While D.C. field is located in the internal plasmatron space, r.f. crosses whole chamber space and applied to the substrate holder. All samples for characterization were synthesized on Si(100) substrates. The Si wafers were cleaned *in-situ* by Ar-plasma etching prior to deposition. The maximum continuous growth time (~ 8 hours) was limited with the hot cathode life time. The multi-step processes were used to grow thick material (200-300 μm).

Characterization

Synchrotron-based x-ray diffraction with small-angle scans in reflection and transmission geometry was applied to study a general symmetry of QUASAM structure, its short-range correlations and density modulation. The stack of 5 free standing QUASAM plates about 200 μm thick each was used to reach the highest possible resolution in this characterization. The synchrotron-based near-edge x-ray absorption fine structure (NEXAFS) was used for a preliminary study of the QUASAM fine structure. The samples were also examined by micro-Raman spectroscopy. In spite of an essential difference in density, stability, mechanical, electronic and other properties of QUASAM, DLN and diamond-like carbon (DLC), no one technique alone allows to distinguish them definitely. It has been demonstrated however, the "S-parameter" in positron annihilation spectroscopy (PAS) clearly discriminates hard and soft modes of DLN films having been deposited upon any substrate [10]. A new two-detector coincidence PAS system have been developed in [11] which improves the peak to background ratio in orders of magnitude and essentially increase elemental specificity of PAS. This new PAS technique provides an unambiguous definition for all mentioned equilibrium and non-equilibrium carbon states, including differentiation of super-light quasiamorphous forms by their specific density. The atomic force microscope (AFM) was used for surface characterization of the DL ASC films

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in nanoscale, and the profilometer MITOTOYO SURFTTEST (vertical resolution 20 nm) -for micro- and macro-scales characterization.

A standard Vickers microhardness tester and Nanoindenter (Nano Instrument, Inc.) were used for hardness measurements. Apart from certain conventional limitations due to the available load and depth ranges of nanoindentation, and optical resolution in the standard Vickers microindentation, both techniques have some limits because of a hierarchical structure and a complex elastic-plastic behavior of QUASAM. The results may be considered as reliable in the hardness range up to about 60 GPa and only as some evaluation above 70 GPa. In spite of this limitation, indentation in the maximum available load range (from 1 mN nanoindentation to 20 N microindentation) provides essential information about material mechanical behavior and stratified arrangement. The 6-direction hardness measurements have been conducted by Vickers to examine the possible anisotropy effects (in plane from 4 cross-section sides, and in normal directions from the growth side and interface side of free-standing square samples). Vickers technique was also applied to cross-section of QUASAM/Si heterostructure including a comparative measurements of QUASAM, silicon and interface. Cracking threshold and fracture toughness of QUASAM and some other hard amorphous and crystalline materials have been compared with the same Vickers indenter. The elastic modulus was measured by nanoindenter and with free standing QUASAM cantilever technique; the results coincide within the experimental error. Multiple Vickers indentation (up to 2000 in one point) was used to study micro-cleavage, cracks propagation and fatigue. Multiple bending of free-standing material around the calibrated steel cylinders was also used to study the critical radius of bending in dependence on material thickness, as well as for the fatigue and residual strain evaluation. Stress in the QUASAM/Si(100) heterostructures was measured by two crystal x-diffraction and two-laser beam methods. The results are in good agreement.

Specific gravity is the parameter of critical importance for characterization and discrimination of carbon phases. Two methods were applied: direct measurements of the physical volume and weight of QUASAM samples and two-detector PAS with comparative measurements of diamond, crystalline graphite and QUASAM. To minimize the thickness variation effects the physical volume for each sample was calculated from 40 measured values: 20 values obtained with high resolution optical microscope (cross-sections of four sides of each plates) and 20 values obtained with electronic digital micrometer "Starrett" (equally distributed points of each plate). Similarly exact area of each sample has been defined by 10 (5+5) measurements of the each plate width in the perpendicular directions. The weighing was conducted with the Ohaus analytical electronic balances AS60 (readability and repeatability 0.1 mg). Estimated maximum error is about 0.05 g/cm³, but the control measurements of monocrystalline silicon with same technique resulted with value 2.3272 g/cm³, e.g. -0.0011 g/cm³ against the real value of 2.3283 g/cm³ [12]. Thermal stability has been studied in open air in the range of 350^o C - 540^o C (up to 30 hours exposure) and in N₂ flow in the temperature range 400^o C - 800^o C. The mechanical properties, the samples weight or micro-Raman spectra of material prior to and after annealing have been applied to study the surface and internal degradation of material at the elevated temperature. The multiple cycles "540^o C → cold water" have been applied to study the thermal shock resistance of free-standing QUASAM and QUASAM/Si heterostructures, as well as the standard silicon wafer of an equal size for a comparison. The chemical resistance was tested during 300 hours in HF, HNO₃, and HCL acids and HF: HNO₃ solution for silicon etching. The material was weighed with the analytical electronic balances prior and after exposure, and QUASAM/Si interface was studied by AFM after the 600 μm thick silicon substrates have been completely etched. The free standing plates of material was tested as the cantilevers and beams.

EXPERIMENTAL RESULTS

Structure

Figure 1 Shows the x-ray scattering of free standing QUASAM. The small-angle scan in reflection geometry [Fig. 1 (a)] shows a broad peak at low angle which indicates density modulation along the normal direction to the samples surface with the length scale of the modulation about 14 Å. The small-angle scan in the transmission geometry [Fig. 1 (b)] shows very little noticeable density modulation in plane. It also displays a uniform and fast decaying low-angle x-ray air scattering profile [Fig. 1 (c)]. The full-scattering profiles of the QUASAM in reflection geometry [Fig. 1(d)] shows both density modulation and short-range correlation in QUASAM, which features are essentially weaker in transmission geometry [Fig 1 (e)]. The sharp peaks are the reflection from residues of the Si substrates - (400) in Fig. 1(d) and (220) and its higher order reflections in Fig. 1(e). These peaks should be compared with the AFM scan of free standing QUASAM interfaces shown below. Figure 2 shows the PAS data. Previous positron results from diamond-like atomic-scale composites (DLASC or "DLN") deposited on various substrates show that regardless of the substrate material used in this study, the hard films have an S value of 0.94 ± 0.05 , and the soft films have a S-value of 0.92 ± 0.05 [10]. A high S value indicates large open-volume structures. QUASAM exhibits even lower densities than the DLN films. Fig. 2a and 2b shows S-E scan from two free standing plates (both $\sim 170 \mu\text{m}$ thick). A high S value indicates large open-volume structures (positron diffusion length is short in these films, $\leq 10 \text{ nm}$, and rules out the possibility of increase in S due to an increase in the number of trap centers). Fig. 2c shows S-E scans from thin DLN films deposited upon the different substrates. Scans display also the interfaces and the respective substrates S-values. A thick film (85 μm) in Fig. 2c corresponds to an intermediate regime of material growth ($\sim 550 \text{ V}$) and possesses an intermediate S-value between DLN ($S=0.94 \pm 0.05$) and QUASAM (0.97 ± 0.1). The QUASAM growth starts with an S value of ~ 0.94 , similar to the DLN films. The S value increases to a new plateau of ~ 0.96 on continued growth. Subsequently, the new structure is stable during the growth (In this samples up to ~ 170 microns). This is evident from the S values of the final growth surface. The transition is reversible as it shows scan 2 (a) from the growth side.

The two-detector coincidence results from QUASAM also suggest the increase in open-volume content. Fig. 2 d shows the annihilation probability density as a function of the longitudinal component of the positron-electron momentum, p_L (for details see ref. 11). The data is plotted as ratio curves, after normalizing to Si. Previous studies have shown that the ratio curves contain distinct peaks and valleys at high momentum corresponding to annihilations with inner shell electrons [11]. The penetration of the positron wave function into the atomic core and the partial annihilation rate of the positrons with different inner shell electrons depend on the lattice structure or the interstitial open-volume. While the position of the peak in the ratio curve is elemental specific, the amplitude is a measure of the positron overlap with inner shell electrons. Fig. 2d shows the ratio curves for diamond, graphite, and QUASAM with different densities. The plot shows a broad peak centered at $p_L \sim 12 \times 10^{-3} m_0 c$. The amplitude of the peak scales with the densities for all the measured materials. It is evident some shift of the peak to lower p_L values with decreasing densities; a more systematic study is needed to understand its physical meaning.

Preliminary NEXAFS studies of QUASAM were focused on a number of representative samples with varying physical properties like hardness. Carbon K (285 eV) and Oxygen K (530 eV) near-edges were obtained. The C-K spectra show features identifiable with sp^3 (diamond) and sp^2 (graphitic) carbon. Most of the carbon is sp^3 bonded. The O-K features resemble quartz with an important exception. SiO_2 has an absorption threshold above 529 eV photon energy.

FIG. 1. The X-ray scattering of free standing QUASAM (a stack of 5 plates with thickness of each ~200 μm). a. Small-angle $th/2\theta$ scan in REFLECTION geometry. A broad peak at low angle ($2\theta=2.08^\circ$ (2) degree, FWHM=2.1 (1) degree) indicates density modulation along the normal direction to the samples surface. The length scale of the modulation is ~14 (Å). b. Small-angle scan in TRANSMISSION geometry which shows a very little noticeable density modulation in plane. c. Low-angle x-ray air scattering profile (uniform and fast decaying air-scattering intensities). d, e. Full-scattering profiles of the QUASAM in reflection and transmission geometries respectively. Fig.1d shows both density modulation and sort-range correlation in QUASAM. The sharp peaks are the reflection from residues of the Si substrates.

Fig. 2 Positron Annihilation Spectroscopy Data. a, b, c. S-parameter vs. positron beam energy. The scans a, b are made from growth side and interface side of two free standing QUASAM plates (the growth of sample 13 was finished in a low temperature regime); c - scans of Diamond-Like Atomic-Scale Composites (DLASC); the thin films were grown at 300 K on different substrates; the 85 μm thick film was grown in an intermediate regime. d. Doppler-broadened spectrum of diamond (1), graphite (2), and QUASAM (samples N6 and N13) at beam energy 10, 20, 30 and 40 kV (3, 4, 5, 6).

QUASAM shows an intense pre-edge absorption feature below 529 eV which extends from 525 to 529 eV and peaks near 527.5 eV. The sharp C-K pre-edge feature at 282 eV is likely due to sp^2 bonded carbon, the strength of this peak is inversely correlated to the strength of the O-K feature [13]. More research is needed to identify the physical and chemical basis for this modification of the electronic structure of the SiO_x in QUASAM.

We have performed a detailed study of the effects of both laser (spot size $\sim 2 \mu m$) and thermal ($400^\circ C \leq T \leq 800^\circ C$) annealing on the structural properties of QUASAM films using micro-Raman scattering [13]. The spectra show two broad peaks with energies $\sim 1350 \text{ cm}^{-1}$ (asymmetric D-peak) and $\sim 1555 \text{ cm}^{-1}$ (symmetric G-peak) which are typical for sp^3/sp^2 amorphous carbon films. The relative part of tetrahedral carbon $sp^3/(sp^3+sp^2)$ ratio in the examined samples has been evaluated in the range 0.6 - 0.75. Shown in Fig. 3 are the Raman spectra of a QUASAM/Si sample of thickness $35 \mu m$. The data are virtually stable for 1 hour annealing at least up to $600^\circ C$. The spectra change slightly only starting from $700^\circ C$ - $800^\circ C$ (Fig. 3). We have found that the structure of these films can be altered (locally with laser annealing with a spatial resolution of $\sim 2 \mu m$) depending not only on the annealing conditions but also on their mechanical properties (hardness and stress).

QUASAM/Si Interface, Growth Front Steadiness and Planarity

Using AFM we have studied of the surfaces/interfaces of QUASAM material over a wide range of thicknesses ($5 \text{ nm} < t_f < 300 \mu m$), including two free standing films [14]. Figure 4(a) shows the AFM scan of the QUASAM/Si interface. The silicon substrate, $\sim 600 \mu m$ thick, was removed by $HF:HNO_3$ etching. Figures 4(b), 4(c) and 4(d) show the scans of the QUASAM growth surface up to thickness $t_f = 300 \mu m$. The QUASAM/silicon surface preserves a nano-scale smoothness ($R_a \approx 2 \text{ nm}$). Scan 4(a) also indicates some residues of the silicon substrate which increase the R_a parameter value up to about 3 nm (these silicon residues may be compared with x-ray scan in Figs. 1(d) and 1(e). For thickness $d \leq 3 \text{ mm}$ the growth front preserves an atomic-scale smoothness in all the examined scales ($1 \mu m^2$, $100 \mu m^2$ and $5625 \mu m^2$ by AFM and $2500 \mu m^2$, 10 mm^2 and 75 cm^2 by profilometer). In an area $< 100 \mu m^2$ the nano-smoothness was preserved in the range of $t_f \leq 40 \mu m$. In the larger scales the roughness is determined by micro defects. Careful study of the film surface and cross-sections shows, the major causes of these defects are micro-crystals of diamond and the growth interruption in the multi-step processes.

Our AFM results show that the nano-smoothness ($\sim 1\text{-}5 \text{ \AA}$) of the QUASAM films has been preserved in both the smaller and larger scanned areas in the wide range $50 \text{ \AA} < t_f < 300 \mu m$. Three major types of morphological features have observed in the larger scan. These are (1)

Fig. 3 The effects of thermal annealing at various temperatures on the Raman spectra of a $35 \mu m$ thick QUASAM/Si sample.

microscratches originating from the substrate. These features are observed in the films with $t_f \leq 50$ nm. They are self-curing during the later steps of the film growth, (2) relatively sharp "defects" having height ~ 500 - 1000 nm and widths ~ 1000 - 2000 nm. These "defects" possess almost the same size in all the studied films but their density increases with film thickness and (3) rounded and slowly textured "defects" observed in the relatively thick films whose size and density increase with film thickness.

Fig. 4(a) AFM image of the substrate side of a $132 \mu\text{m}$ thick free standing QUASAM film.

Fig. 4(b) AFM image of the growth surface of a $110 \mu\text{m}$ thick free standing QUASAM film.

Fig. 4(c) AFM image of the growth surface of a $132 \mu\text{m}$ thick free standing QUASAM film.

Fig. 4(d) AFM image of the growth surface of a $300 \mu\text{m}$ thick QUASAM/Si film.

Thermal Stability and Thermal Shock Resistance

Thermal stability is a crucial characteristic of construction material for MEMS. Material must withstand a long-term service in a possible sever environment during the MEMS work, a medium term exposure in a broad temperature range of MEMS fabrication, and it must be compatible with silicon in such conditions. The Tables 1, 2, 3 show the results of QUASAM examination.

Table 1. Annealing in Open Air (two samples)

No cycles	t , °C	Annealing time: τ , hours			Weight, 10^{-4} g		H , GPa
		τ_{cycle}	$\tau_{\Sigma}(t)$	$\tau_{\Sigma\Sigma}$	$W_0=$ 326	$W_0=$ 342	
1	400	3	3	3	326	342	24
2		3	6	6	326	342	24
3		4	10	10	327	342	24
4	470	0.3	0.3	10.3	326	342	24
5	470	0.5	0.8	10.8	326	342	24
6	470	0.3	1.1	11.1	326	342	24
H=24 GPa at $t=450$ °C							
7	470	0.2	1.3	11.3	326	342	24
8	470	0.2	1.5	11.5	326	342	21
H=21 GPa at $t=450$ °C							
9	470	0.2	1.7	11.7	326	342	
10	470	2	3.7	13.7	326	342	
11	470	2	5.7	15.7	326	342	
12	470	3	8.7	18.7	326	342	
13	470	3	11.7	21.7	326	sam-	
14	470	2	13.7	23.7	327	ple	15
15	525	1	1	24.7	326	cutted	14
16	538	1	2	26.7	325	for	
17	538	2	4	27.7	326	study	13
18	520	3	7	30.7	326		11
19	520	3	10	33.7	324	Surface cracks

Figure 5. The Annealing Timing for Table 1

Table 2. Hardness after annealing, 800 K, a limited air access

τ_c	τ_{Σ}	H, GPa	
		Surface	In plane
as grown		40	40
0.5	0.5	40	
1.0	1.5	40	
3.5	5.0	40	
5.0	10.0	12.5±0.5	
12	22.0	Oxide	40
8.0	30 h	12.5±0.5	40

Table 3. Thermal Shock Resistance 800 K - cold water cycles

Structure	Cycles	Result
QUASAM	20	no damage
Si/QUASAM	8	fractured
Silicon	6	fractured

The coefficient of thermal expansion of QUASAM is in the range of 1.6×10^{-6} - 1.7×10^{-6} depending on growth conditions. Both, mechanical properties of QUASAM and the thermal expansion coefficient are virtually constant at least up to 700 K. Long-term annealing at 800K does not result in any visible decrease of mechanical properties of this form of carbon (which corresponds to the micro-Raman examination). Thick material was not yet tested above 800°C, but the 1mm - 3 mm films have been tested as the components of heterostructures Si/QUASAM up to 1250°C in SiCl_4 -HCl flow during 2 hours. In spite some changes of their fine structure, the films have preserved their structural uniformity and the masking ability in the silicon selective etching and selective epitaxial growth process.

Mechanical Properties

Figure 6 is a typical micro-photograph of the QUASAM/Si(100) heterostructures. The left light area is the silicon (whole thickness is 600 mm), and dark right area is the QUASAM layer (whole thickness is 250 mm). The splittings in the silicon area are the results of the Vickers indentations with load 0,6 N. Small points in the QUASAM area are also the results of the Vickers indentations but with load 1.1 N and 1.65 (no one indentation was resulted with splitting). Indentation exactly in interface have splitted in silicon area only.

Fig. 6. Microphotograph of QUASAM/Si Heterostructure

Figure 7 shows a general distribution of the normal (both directions) and *in-plane* hardness for whole range of the synergetic regimes of the low-stress QUASAM growth. Typical values of mechanical parameters in the growth conditions $T = 410 \pm 10^\circ\text{C}$, $U = 100\text{V}$ are: $H_v = 30 \pm 5\text{GPa}$, $E = 190 \pm 35\text{GPa}$, fracture toughness by Lawn-Pharr [15,16] $K_{\text{IC}} = 14 \pm 1\text{MPa}\sqrt{\text{m}}$. The radial cracking threshold $w_r \geq 10\text{N}$ in normal directions (from both, interface and growth side), $w_r \geq 3\text{N}$ in plane, the cone cracking threshold $5\text{N} \leq w_c \leq 10\text{N}$ in growth side, $3\text{N} \leq w_c \leq 5\text{N}$ in interface, and $1.6\text{N} \leq w_c \leq 3$ (unlike other hard materials [16] due to a stratified

QUASAM FIG. 7. Hardness in normal directions and structure. The "cone" cracks are and shallow in plane in the load range of 1mN - 20 N. (1-3 mm in depth), no propagation is observed.

Less than 2% of 2000 tests exposed cracks under loads 0.65 N. Even 1000 indentations in the same point with the 0.65 N load usually do not result in cracks. [the silicon wafer (100) with same indenter had $w_r = 0.38\text{N}$, fused quartz $w_r = 1.7\text{N}$, crystal quartz $w_r = 0.7\text{N}$, natural topaz $w_r = 0.65\text{N}$, garnet $w_r = 0.60\text{N}$]. The maximum hardness having been recorded for low stress material (with nano and micro-indenters) is $H_v = 56-57\text{GPa}$. However an essentially more strong real time control is necessary to realize such a reproducible growth. In the high stress material ($s_s > 1\text{GPa}$) the values $H_v \geq 70\text{GPa}$ and $E = 525\text{GPa}$ have been reached. However the high stress material possesses a limited mechanical stability, and probability of its self-fracture increases with its thickness. Low-stress material never revealed any instability.

The free standing material was tested in the cantilevers and beams geometry in range of thickness 5 mm - 112 mm, and length up to 4 cm. The critical radius of bending of may be defined as the function of thickness "d" with an empirical relation $R^* \sim 100d^{1.2}\text{mm}$. QUASAM foil is quite flexible at the thickness $d < 30\text{mm}$, it is still preserves some flexibility and a spring-like behavior at the thickness $d \leq 60\text{mm}$, but becomes brittle at the thickness $d \geq 100\text{mm}$. No noticeable residual stress was recorded after 2000 bends with radius $R > R^*$.

Specific gravity of QUASAM depending on the growth conditions is in the range of 1.3 to 1.7 g/cm^3 . The typical QUASAM density is about 0.4 relative to the diamond. In spite of the low density Atomic Force Microscopy does not reveal any pores over $\sim 0.3\text{nm}$ in diameter. With the maximum available accuracy a full isotropy in plane and a slight one-axis anisotropy with usually "harder" normal direction were demonstrated. Coefficient of anisotropy $K_a = 1.2-1.4$.

The 300 hours exposure in strong acids including the standard Si etching agent ($\text{HF} + \text{HNO}_3$) didn't result with the samples weight losses or a visible surface change.

Non-alloyed QUASAM possess electrical resistivity in the range of $10^6-10^{10}\text{Ohm.cm}$ where the highest level corresponds depending mainly on the growth temperature about 280°C . It may be alloyed with different metals up to resistivity $\sim 2 \times 10^{-4}\text{Ohm.cm}$ [17]. The QUASAM growth may be started from or reversed to the DLN deposition with resistivity $2 \cdot 10^{12}\text{Ohm.cm}$.

Deposition upon microceramics (substrates for the hybrid IC) and steel have resulted

with similar properties of QUASAM and the respective interfaces.

IV. CONCLUSION

The super-light hard quasi amorphous sp^3/sp^2 carbon (QUASAM) is synthesized in the synergetic conditions of thermal and impact activation of the growth reactions. The synergetic approach allows to decrease voltage and increase the energy effectiveness and growth rate in order of magnitude relative to DLC. Material combines hardness ≥ 30 GPa, modulus ~ 200 GPa, stress ≥ 0.05 GPa, fracture toughness ≥ 10 MPa $\sqrt{m}$, cracking threshold ≥ 3 N, long-term stability $\geq 600^\circ\text{C}$, extremely high thermal shock and chemical resistance with density below of all the known hard materials ($1.4 - 1.65$ g/cm 3). Its mechanical properties and thermal expansion are virtually constant in the range of 300K - 700K. QUASAM is free from pores from the thickness of 3-5 nm and preserves uniformity over 100 mm including large free standing beams with length ≥ 1 cm. The following characteristics make provides new carbon with a compatibility with IC technology: growth temperature 200- 450 $^\circ\text{C}$, excellent interface and extremely high mechanical and thermal-shock resistance of QUASAM/Si heterostructures, nano-planarity of the growth (at least up to 30 mm) and interface (after the silicon substrate etching), high-temperature resistance to SiCl_4 -HCl environment. It is also reasonable to suggest, this new carbon structure possessing 60% free volume space and a planar arrangement may be prospective for nanoelectromechanics. Work performed, in part, by the US DOE under contract no. DE-AC02-76CH00016.

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