Advances in Science and Technology Vol. 48 (2006) pp. 142-150
online at http://www.scientific.net

Diamond loudspeaker cones for high-end audio components

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Keywords: CVD diamond, membrane, loudspeaker, acoustical simulation

Abstract

Conventional loudspeaker membranes made of metal or synthetic material such as fabric, ceramics or plastics suffer from nonlinearities and cone breakup modes at fairly low audio frequencies. Due to their mass, inertia and limited mechanical stability the speaker membranes made of conventional materials cannot follow the high frequency excitation of the actuating voice-coil. Low sound velocity causes phase shift and sound pressure losses due to interference of adjacent parts of the membrane at audible frequencies.

Therefore, loudspeaker engineers are searching for lightweight but extremely rigid materials to develop speaker membranes whose cone resonances are well above the audible range. With its extreme hardness, paired with low density and high velocity of sound, diamond is a highly promising candidate for such applications.

We report on the realization of dome shaped CVD diamond membranes by deposition on curved silicon substrates. Domes with diameters between 20 and 65 mm and with a thickness ranging from 50 to 120 µm were prepared. After deposition, the substrate is dissolved and the rim of the diamond dome is cut by laser scribing. Free standing diamond membranes are mounted onto dynamic voice coils and integrated into tweeter and/or midrange driver chassis. Extended tests and optimisations led to loudspeaker systems that show a second and third harmonic distortion behaviour in the important frequency range between 3 to 10 kHz that is reduced by 40% in comparison to already excellent established values obtained with sapphire membranes. Cone resonance frequencies of CVD diamond membranes are increased by a factor of two, as predicted by simulations.

Introduction

Diamond membranes – in theory – have always been the dream of loudspeaker engineers since the mechanical properties of diamond are close to those of an ideal hypothetic material which would have an infinite Young's Modulus and – at the same time – a vanishing density. However, since nature doesn't offer diamond in the shape of membranes and the *High Pressure High Temperature* synthesis only provides small crystallites, acoustic engineers were compelled to use ordinary materials like aluminium or sapphire for high end tweeters.

With the development of CVD technologies to produce large area diamond discs with properties matching those of the best natural diamonds [1,2] and molding techniques to deposit CVD diamond on preshaped substrates [3,4,5], diamond domes for loudspeaker applications became feasible. After early suggestions by Sumitomo [6] no further development was done until in 1999 when Fraunhofer IAF and Thiel & Partner GmbH, an audio equipment manufacturer specialized in hard material loudspeaker membranes, entered a cooperation aiming to develop a novel high frequency tweeter with a diamond membrane. This cooperation succeeded in launching its first commercial tweeter system in the year 2000. Nowadays leading audio system manufacturers such as Avalon Acoustics (USA), Lumen White (Austria), Mårten Design (Sweden) and Kharma (Netherlands) are using these tweeters for their high end loudspeaker systems

In this paper we describe the deposition and machining of a diamond membrane, its mounting on a voice-coil and its integration into tweeter chassis. We will assess the mechanical and acoustical properties of these systems by FEM simulations and compare their result with sound pressure measurements. Finally we will discuss the effect of frequencies above the audible range (>20 kHz) on the auditor.

Preparation of CVD diamond tweeter membranes

To prepare dome shaped diamond membranes, polycrystalline CVD diamond is deposited onto preshaped substrates. The possibility to make three dimensional diamond devices by simply replicating a substrate has been used by a number of scientists to create for example anti reflection structures by the moth eye effect [4] or optical diamond lenses e.g. for CO_2-laser surgery [3]. For these kinds of applications generally silicon is used as a substrate since it is easy to machine and polish, it enables the nucleation of diamond and is easily dissolved in acid after diamond deposition. Figure 1 illustrates the processing steps to prepare dome shaped CVD diamond membranes.

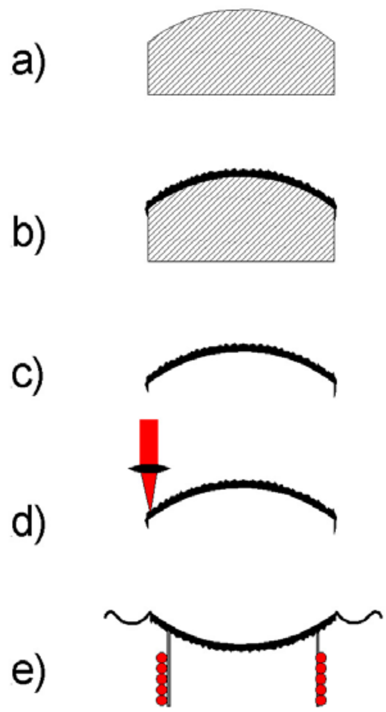

Fig.1: Processing steps to prepare dome shaped CVD diamond tweeter membranes. a) preshaped silicon substrate. b) substrate after deposition of CVD diamond. c) diamond dome after separation from the substrate. d) laser cutting of diamond dome. e) diamond membrane assembled with surround and voice coil former.

For growing thick free standing CVD diamond, a microwave plasma CVD reactor with ellipsoidal cavity [7] that provides stable deposition conditions is used. As standard growth conditions we use a microwave power of 6 kW at a frequency of 2.45 GHz, a substrate temperature between 700 and 900°C and a pressure ranging from 100 to 200 mbar. The feed gas is 1-2% methane in hydrogen. After CVD diamond deposition (Fig.1b) the silicon substrate is dissolved in acid (Fig.1c) and the rim of the now free standing membrane cut using a Nd:YAG laser scriber (Fig.1d). As a last step the completely machined membrane (Fig.1e) is mounted onto a voice-coil, fixed with a surround and integrated into a tweeter and/or midrange loudspeaker driver chassis (Fig.2).

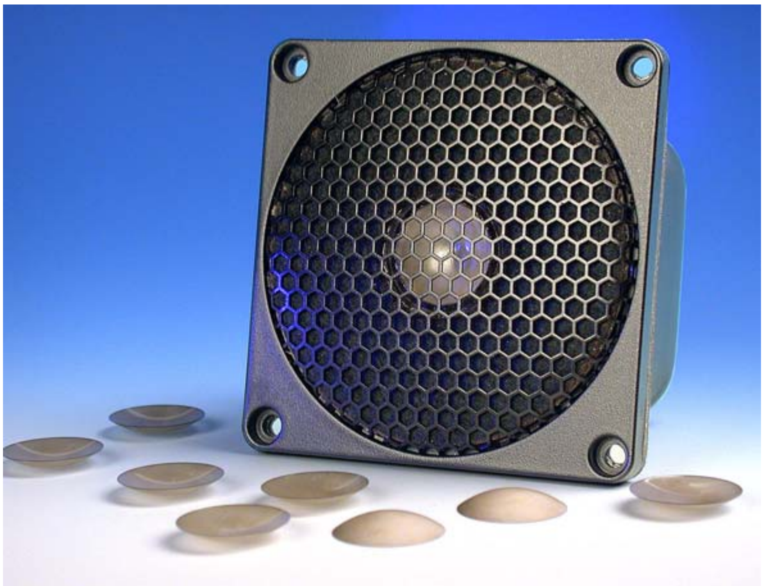

Fig.2: Free standing dome shaped CVD diamond membranes (front) and a D20-tweeter from Thiel & Partner equipped with a CVD diamond membrane.

Mechanical and acoustic properties of diamond tweeters

To describe the acoustic properties of loudspeakers, a commercial finite element modeling program *(Finecone)* that calculates amplitude response and impedance in radial symmetry was used. As a matter of fact, there are also non axial-symmetric modes present, but since these are higher in frequency than the cone breakup (i.e. the first and dominant natural oscillation of the membrane voice coil configuration), these do not play a dominant role and therefore we do not want to go in further detail here. As a first approach and to check the reliability of these simulations, the resonance frequencies f_n of a flat membrane that are given analytically by [8]:

$$f_n = \frac{k_n}{2\pi}\sqrt{\frac{Et^3}{12\rho r^4(1-\nu^2)}} \tag{1}$$

were calculated.

In equation (1) r is the radius and t the thickness of the membrane, E its *Young's Modulus*, ν its *Poisson's Ratio* and ρ its density. k_n is the constant for the n^{th} natural oscillation ($k_1 = 10.2$, $k_2 = 21.3$, $k_3 = 34.9$, …). According to equation (1) the natural frequencies are proportional to the square root of E/ρ, i.e. a good membrane should be stiff and light. For a flat 60 µm thick diamond membrane 20 mm in diameter with E = 1140 GPa, ν = 0.1 and ρ = 3.51 g/cm^3, the first natural frequency occurs according to (1) at a frequency of as low as 5.09 kHz. For a simple rim-supported membrane the simulated result equals exactly the one analytically postulated. A real tweeter membrane however is not free standing but attached to a voice-coil former and clamped to a centralizing surround, both adding mass and increased damping to the whole structure. A cross section of a typical configuration used for simulations with *Finecone* is shown in figure 3.

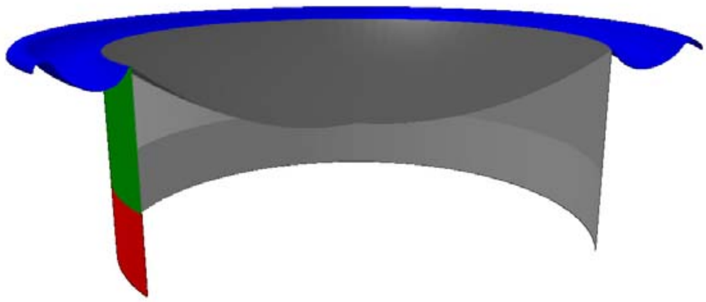

Fig.3: Cross section through a tweeter membrane attached to a former (green) on top of an actuating voice-coil (red) and clamped to a surround (blue).

For the fixed membrane, the cone breakup occurs at a lower frequency, basically due to the fact that combined oscillations of former and dome are lower in frequency than oscillations of the isolated dome itself. Besides the material of the membrane, also its geometry and the properties of the attached surround and voice coil former play a crucial role for its overall performance. The sag height of the membrane has a very strong influence on the sound pressure level (SPL). Figure 4 displays the frequency dependence of the calculated SPL for diamond tweeter membranes fixed as shown in figure 3 for various sag heights.

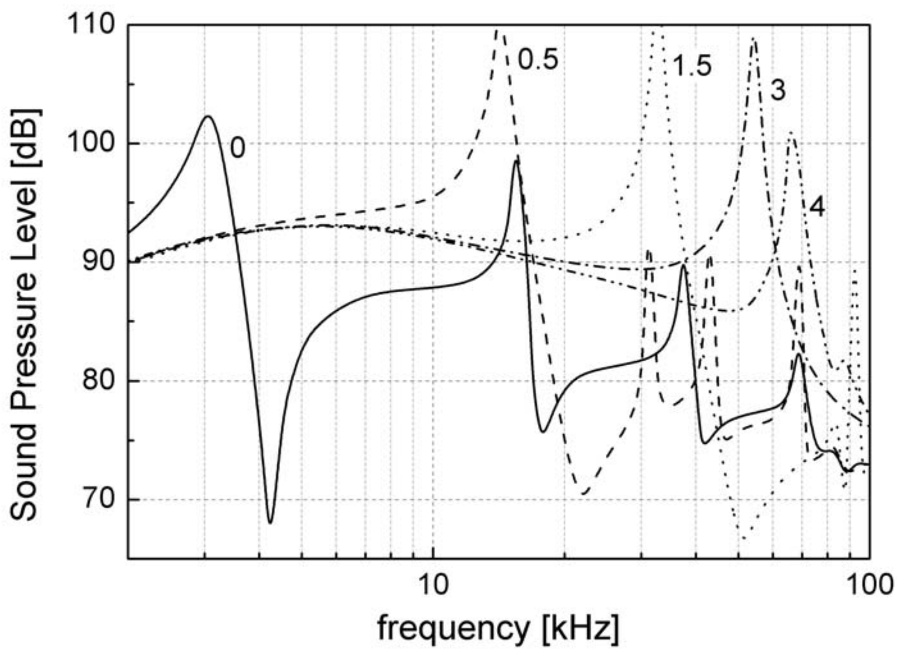

Fig.4: Sound pressure level (SPL) in a distance of 1m vs. frequency for a 20 mm diamond membrane with increasing sag height ranging from a flat membrane to a membrane with a sag height of 4 mm.

Although flat membranes would be highly desirable in terms of vanishing *phase loss* (see below) figure 4 clearly states that the sag height has a strong influence on cone breakup frequencies and high frequency SPL. A comparatively moderate sag height of 0.5 mm increases the frequency of the first cone breakup almost by a factor of 5 from 3 kHz to 14 kHz with further increase to almost 70 kHz given a sag height of 4 mm. Inversely proportional to the sag height appears the high frequency SPL and the peak energy of the cone breakup, suggesting an optimum of 3.0 to 3.5 mm sag height. Cone breakup modes are always associated with a significant increase in harmonic and non-linear distortion, also with undesired lobing of sound pressure. In terms of sonic quality therefore cone breakup modes should be pushed as far away as possible from the audible range to avoid any kind of subharmonic interference.

The membrane thickness has a moderate influence on the SPL, the thicker and thereby stiffer the membrane, the higher the cone breakup, which is desirable. However for a thicker and heavier membrane the total SPL is reduced; an optimum can be found for the D20-tweeter in between 50 and 60 µm. Figure 5 compares the SPL of an aluminium, a diamond and a infinitely stiff dome (∅: 20 mm, h = 3.5 mm) of the same mass. Surprisingly at first sight is the fact that the infinitely stiff membrane shows a pronounced dip in the response around 90 kHz. This is a result of phase interferences or phase losses, i.e. for inverted dome shaped membranes matters that the sound generated at the centre of the membrane reaches the auditor later than the sound generated at the rim, thus enabling the sound waves to interfere and extinguish each other at certain frequencies. This effect is strongest if the competing regions have about the same area.

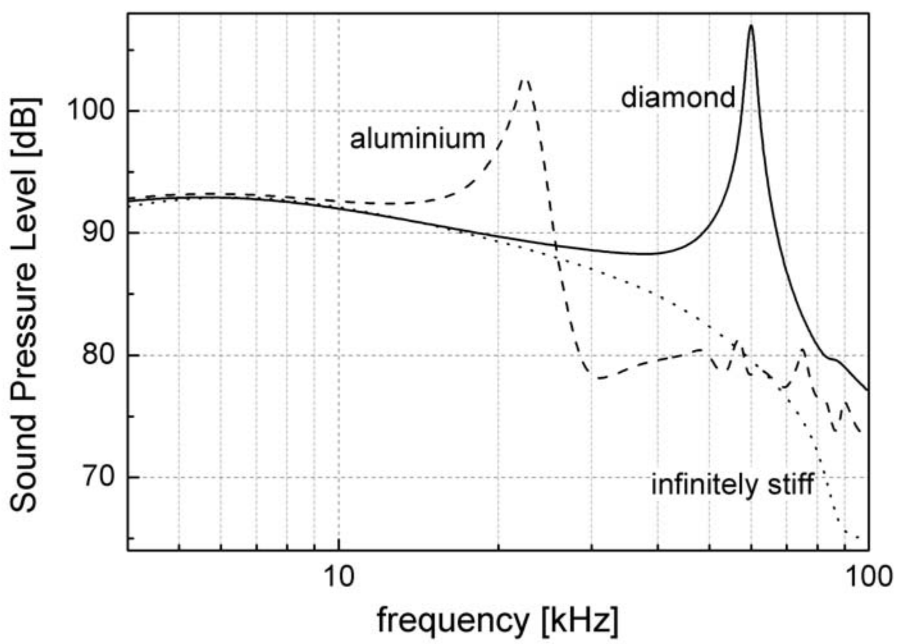

Fig.5: SPL vs. frequency for an aluminium, a diamond and an infinitely stiff membrane, all of the same mass.

In the case of diamond, the cone breakup at 60 kHz overrides phase losses and as a result prevents the sound pressure from decreasing. The aluminium dome suffers from cone breakup at a rather low frequency of 22 kHz although this is well above the audible range. We will discuss in the next section whether or not this has an influence on the auditor.

Figure 6 finally shows the measured sound pressure level and total harmonic distortion (THD) for D20-6 tweeter with a diamond membrane. As predicted by theory, the cone breakup occurs at a frequency of around 65 kHz.

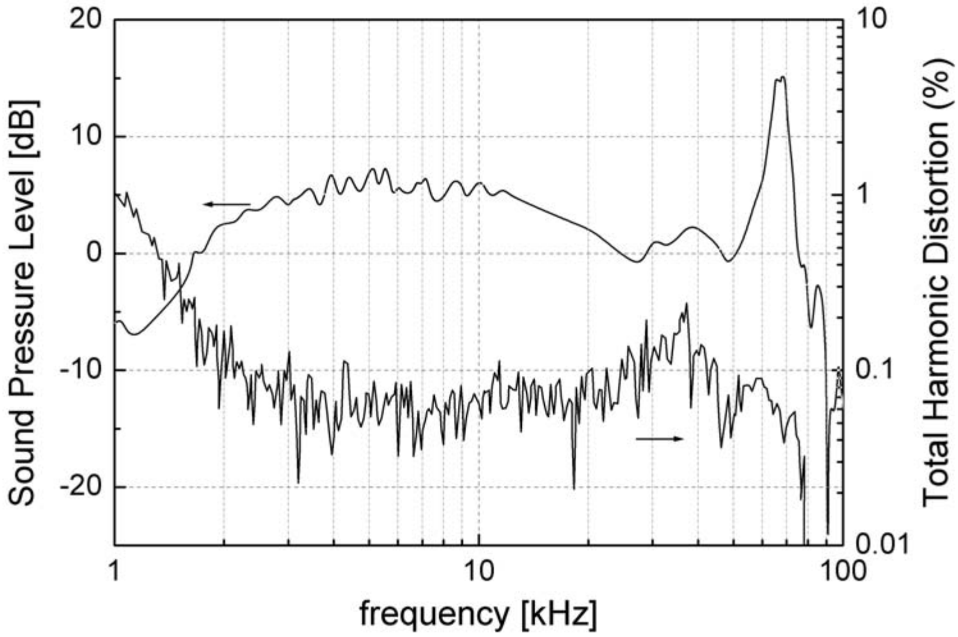

Fig.6: Sound Pressure Level and Total Harmonic Distortion vs. frequency of a D20-6 tweeter, measured with B&K 4138 microphone in app. 10 cm of distance and R&S UPD Analyzer processing.

One of the most crucial features of the diamond membrane is the fact that the harmonic distortion is greatly reduced as can be seen from figure 6. In the most important range from 3 kHz to 10 kHz, the total harmonic distortion in general is below 0.1 % with the exception of occasional spikes. The mean smoothed value is near 0.07 %, a value we have not been able to achieve with even the best conventional tweeters. Common THD values of ordinary tweeters are one order of magnitude higher.

Commercially available domes have sizes of 20 mm, 25 mm, 30 mm and 50 mm. Laboratory samples of 63 mm diameter have been produced. As expected, a similar picture as for the mentioned 20 mm domes appears with larger cones. Figure 7 shows measured and simulated SPLs of a 50 mm diamond and sapphire cone. In good agreement with the simulation, the cone breakup occurs for the diamond dome at about 30 kHz, almost one octave higher than for the sapphire cone of the same size. In addition the total harmonic distortion (THD) of a diamond cone is way better than with any kind of conventional membrane material, thus improving the sonic quality of mid frequencies.

Since the large diamond cone still has a bandwidth that reaches well above the audible range, it can be used as tweeter with a very low cross-over point. Frequencies as low as 400 Hz appear possible, thus coming closer to the ideal sound transducer: a single-point, time-coherent minimal-phase system covering the entire audio band.

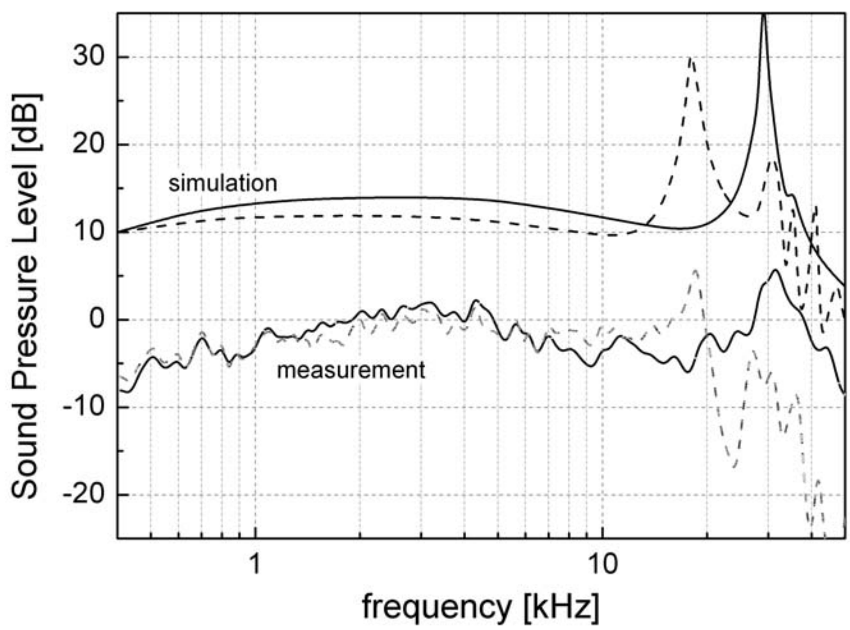

Fig.7: Measured and simulated (20 dB offset) SPL vs. frequency for a diamond (solid) and a sapphire midrange driver (dashed), both 50 mm in diameter.

Conclusions

Membranes made of CVD diamond enable audio frequencies of up to 100 kHz to be transmitted, values that are not achievable with any other material.

So far, the question whether or not frequencies above 20 kHz have any influence on the auditor had been of concern only for a few high end audiophiles, who do not use conventional CDs containing almost no acoustic information above 20 kHz. However the breakthrough for SACD and DVD audio format with sampling rates of 192 kHz or higher is only a matter of time. Do we all need to buy new speakers with diamond tweeters?

The perception of frequencies beyond 20 kHz has been lively discussed in the past. It is common understanding now among audiophiles that extended reproduction chains improve the overall performance. The degree of frequency extension and the influence on clarity, ambience and neutrality are still controversially disputed. However various researchers proved that orchestral music contains significant spectral energy in frequencies up to 100 kHz, Oohashi [9] provided evidence that inaudible high-frequency sounds have a significant effect on human brains. This has been called "the hypersonic effect". Although more research has to be done on the influence of ultrahigh frequencies on the auditor, the audio community agrees on the fact that systems that are linear up to highest frequencies sound more detailed, effortless and produce a more realistic sound stage. This is mirrored by the steadily growing demand for speakers with diamond membranes.

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