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(54) SONIC PULSE GENERATOR

(71) We, INTERNATIONAL BUSINESS MACHINES CORPORATION, a Corporation organized and existing under the laws of the State of New York in the United States of America, of Armonk, New York 10504, United States of America, do hereby declare the invention for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:-

This invention relates to sonic pulse generators.

According to the invention there is provided a pulse generator comprising a body having or being acoustically coupled to an energy absorbing layer, an energy source operable so to direct pulses of non-mechanical energy into the energy absorbing layer as to subject the energy absorbing layer to mechanical vibration which propagates into the body, and a vibration limiting medium acoustically coupled to the energy absorbing layer to limit the vibration of the energy absorbing layer in a direction opposite the propagation of vibration into the body whereby the vibration limiting medium enhances the propagation of vibration into the body.

The invention will be further explained by way of example with reference to the accompanying drawings in which:-

FIGURE 1A shows a sonic pulse generator according to the invention, and

FIGURES 1B and 1C show alternative forms;

FIGURE 2 shows graphs used to explain the invention;

FIGURE 3 shows a flaw detection application of a sonic pulse generator according to the invention;

FIGURE 4 shows signals illustrating output from the flaw detector of Figure 3;

FIGURE 5 shows a sonic pulse generator with a part inverted for comparative tests;

FIGURE 6 shows another sonic pulse generator according to the invention;

FIGURES 7 and 8 show embodiments of the invention using pulsed voltage sources;

FIGURE 9 shows an embodiment using a pulsed ion beam source; and

FIGURE 10 shows an embodiment using an x-ray source.

FIGURE 1A shows laser 9 providing a pulsed laser beam 10 directed through lens 11 to focus upon an evaporated energisable i.e. energy absorbing film 13 of tungsten or molybdenum about 2000 Å thick deposited upon the lower surface of a dielectric thin plate 12 of a material such as polished glass, quartz, or sapphire (Al_2O_3) transparent to laser beam 10. Film 13 is acoustically bonded with a solid or viscous liquid acoustic bonding agent 14 such as a propylene glycol, silicone oil, stopcock grease, epoxy resin, wax, or Canada Balsam to a solid sample 15 composed of a material selected from quartz, Al_2O_3 (sapphire), ceramics, metals, semiconductors, dielectrics, or a container of liquid. A ceramic piezoelectric transducer-receiver 16 sensitive to compressional waves such as a Panametrics, M 116 20 Mhz ± 5 Mhz can be used. Its output may be amplified and displayed either on an oscilloscope or an x-y recorder used in conjunction with the output of an integrator. In a particular experiment using the above equipment and 5 nanosecond laser pulses, incident power levels are of the order of 350W (corresponding to only 2×10^{-6}J).

In operation of this embodiment of the invention then, a pulse of laser light 10 or other optical energy is applied to a thin film 13 of an energy absorbing material which, when energized, causes mechanical (acoustic) waves to be generated in body 15 with which it is in intimate contact. Absorbing layer 13 is acoustically in contact with "clamping" medium 12 which is acoustically "clamped" to it in the sense that the mechanical vibration of the absorber layer is clamped or limited by the "clamping" medium, which can be a clear fluid or a transparent solid such as quartz, SiO_2, etc. The ideal is for the clamping medium 12 to reflect all mechanical motion generated by absorbing layer 13 back into the absorbing layer by pressing against it at all points without a gap as a fluid can do or as a bonded solid can do if bonded sufficiently. Thus, through "clamping", film 13 is confined at that surface, and when it attempts to expand, its expansion is constrained so greater vibration in the solid body is produced, and a greatly enhanced elastic wave 8 is generated and launched into the solid body 15. Transducer 16, which is sensitive to the vibration, produces an output on oscilloscope 20.

Alternatively, film 13 can be deposited upon sample 15 and plate 12 can be bonded to film 13 by acoustic bonding agent 14 as shown in FIG. 1B.

In still another embodiment shown in FIG. 1C, film 13 is replaced by a thin plate 13' of energy absorbent material which is bonded by agent 14 above to plate 12 and below to material 15.

FIG. 2 shows the detected acoustic amplitudes for clamped operation of a device in accordance with FIG. 1A in response to a 5 nanosecond pulse laser excitation of a 2000Å thick Mo film 13 deposited upon a 0.025 cm thick plate 12 of Al_2O_3 bonded by propylene glycol to a 5 cm diameter, 0.95 cm thick fused quartz disc 15. For operation to produce the unclamped output in FIG. 2, plate 12 with the Mo film 13 is inverted to bond the surface 17 of plate 12 to sample 15 by means of propylene glycol. The clamped device curve in FIG. 2 shows recorder traces of 20 MHz acoustic waves generated by a 5 nanosecond laser pulse (rhodamine 6G) incident on the Mo film 13. The peak at time $t = 0$ is the optically detected laser pulse which provides a reference time. The signal near $t = 1.8\ \mu s$ is the acoustic wave detected by transducer 16.

FIG. 2, unclamped, shows the results for the inverted Mo film 13 with the acoustic waves being generated at the free, unconstrained surface of film 13. A ratio R is obtained by comparing peak-to-peak amplitudes in FIG. 2 of the clamped-to-the-unclamped curves which in this case yields a value of R of about 95, or a 40 db increase.

When the same experiment was performed using chromium for film 13, a 46 db increase was achieved.

Using a thick plate 12 (0.16 cm), the results were similar to the results discussed above in connection with FIG. 2 since thickness is not critically determinative of results for thicknesses greater than the acoustic wavelength. Accordingly, in this case, the mechanical resonance of the constraining medium did not appear to affect the results.

Theoretical Considerations

The amplitude enhancement observed here can be estimated from the solution to the one-dimensional stress-strain relationship when the thermal expansion of the absorbing layer is included as a driving term. The equations as given in White, *supra*, have the form,

$$\sigma_{xx} = \rho v^2 \varepsilon_{xx} - B\alpha\theta \qquad (1)$$

and

$$\rho \frac{\partial^2 u}{\partial t^2} = \rho v^2 \frac{\partial^2 u}{\partial x^2} - B\alpha \frac{\partial \theta}{\rho x}. \qquad (2)$$

Here, σ_{xx} is the x component of the stress tensor, ε_{xx}, the corresponding strain, ρ, the density, B, the bulk modulus, α. the thermal coefficient of expansion, θ, the temperature rise above ambient, u, the particle displacement and v, the compressional wave velocity. White, *supra*, has solved Eq. 2 for the case of a periodic driving term, incident at the surface of a uniform semi-infinite medium. The solutions to the instant problem are complicated by both the pulse shape of the driving term as well as the multiplicity of boundaries resulting from the different media comprising the structure. Based on preliminary estimates of a more exact treatment, the ratio, R, should fall near the range of values obtained from the perfectly free and perfectly clamped cases of White, *supra*.

For those limits, one obtains from White

$$R = \frac{v}{(2\pi K f)^{1/2}} \qquad (3)$$

with K the thermal diffusivity of the absorbing film and f the frequency of excitation. In the experiments described herein, f is determined by the receiver-transducer which is tuned to 20 ± 5 MHz. The absolute amplitude of the detected elastic wave will, of course, depend in addition on the thermal parameters of the absorbing medium as well as the Fourier component of the incident pulse shape at the frequency, f. For Mo, Eq. 3 yields $R = 75$ compared to an experimental value of 95 (see FIG. 2) in reasonable agreement with theory under the present approximations and estimated value for K.

Flaw Detection

Thermoelastically generated elastic waves can be employed for flaw detection in a structure designed to simulate a laminate. The structure shown in FIG. 3 consists of a 1 cm long, 1.6 cm diameter aluminum cylinder 18 with polished ends. To the top surface, a 4 mil microscope cover slide 19 is bonded to simulate a lamination. Into the top Al surface, several 0.04 cm diameter holes 20 of equal depth separated by 0.08 cm were drilled to simulate flaws at the laminate interface. Elastic waves are generated using a 10 mil Al_2O_3 substrate 12 and Mo film 13 combination as in FIG. 1A, with the Mo film 13 bonded to the cover slide 19 by acoustic bonding agent 14 - see previous discussion. The experiment is carried out in an optical microscope with the pulsed rhodamine laser focused to approximately a 0.03 cm spot size by lens 11. Optical scanning is achieved by manual movement of the microscope stage 60 shown in phantom in FIG. 3 for transverse movement of cylinder 18 and is well known in the art. In this manner, elastic waves can be generated anywhere along the top surface of the sample and detected at the opposite surface by the Panametrics transducer 16 (active diameter, 1/8"). The detected patterns are shown in FIG. 4 by curves a-d for regions corresponding to optical absorption directly above and in between the defects. Curves a and c show results for scanning over adjacent holes. Curves b and d apply to scanning spaces between holes. Note, for example, that the maximum excursion from the baseline in curves a and c is positive while negative in curves b and d. The flaws at the laminate interface are distinctly visible in the transmitted acoustic pulse without the use of any additional signal processing. Flaw detection using optically generated elastic waves is achieved through this rather simple example. The scannability feature should make the present scheme particularly attractive for evaluation of samples, permitting a single receiver to be bonded at the back surface for the detection of acoustic waves generated anywhere on the front surface. Note that by simply changing the focal size of the laser spot on the absorbing medium, the diameter of the acoustic source can be changed. For example, lens 11 in FIG. 3 can be adjusted vertically by mechanical linkage 112 shown in phantom as is well known in the art. In this way, the acoustic beam can be readily changed from a plane wave ($\lambda/d << 1$) to a spherical wave ($\lambda/d >> 1$) depending on the requirements of the application, where λ is the acoustic wavelength and d the diameter of the acoustic source. This can produce a very narrow collimated beam when λ/d is on the order of 1. The beam can be scanned by moving the substrate beneath the beam as above or by scanning the beam across the substrate as is well known in many optical scanning systems.

Tungsten Absorber Layer

Another example of apparatus tested in connection herewith includes use of a tungsten absorber layer 13 on plate 12 which is bonded to quartz substitute 15. Here again, acoustic waves were generated using 5 nanosecond pulses of rhodamine 6G laser light. Firstly the plate 12 and layer 13 are arranged as shown in Figure 5 so that the pulses fall directly on layer 13. The resulting acoustic amplitude is measured by a receiver centered at 20 MHz. Then the plate 12 and layer 13 are inverted, and the quartz cylinder 15 is mechanically contacted to a tungsten film 13 by means of propylene glycol 14 as an acoustic bond. The ratio of amplitudes measured is 1:240 corresponding to a power ratio of improvement for the clamped case of 48 db.

Aluminium on Mylar Polyester

Aluminium films 13 have been deposited onto Mylar (Registered Trade Mark) polyester plates 12 with the plate acting as the free surface as in Figure 1A. The A1 film 13 is bonded by an acoustic bonding agent of propylene glycol to a quartz samp 13 15, and a 200 times greater signal is observed compared to the Figure 5 arrangement with the A1 acting as a free surface.

Clamping Materials

Clamping materials for use with optical energy sources include transparent or semi-transparent solid films or plates composed of SiO_2, perylene, or SiO used as overlay on the energy absorbing surface. Clamping materials for use with electrical energy sources (e.g. as discussed hereinafter with reference to Figures 7 or 8) include any of the above as well as opaque materials which are of high electrical resistivity, such as semiconductive plates or overlays, made of Ge, ceramincs, etc.

Intrinisic Absorbing Body

In Figure 6, a system is shown in which a sample 28 is composed of a highly energy absorbing material. If source 29 is a visible laser, then sample 28 is composed typically of aluminium, molybdenum, tungsten, silicon, or germanium. Sample 28 is claimped directly to plate 12 by acoustic bonding agent 14. The energy is absorbed at the highly absorbent surface of body 28 which faces bonding agent 14 and plate 12.

Elastic Waves

The frequency of the elastic waves obtained in any system in accordance with this invention will be determined predominantly by the Fourier transform of the energy pulse and the detailed optical or thermal, and elastic parameters of all of the media comprising the structure.

Figure 7 shows a sonic pulse generator transducer excited by electrical energy rather than optical energy. A block of material 15 has the usual piezoelectric transducer 16 attached to it. A block 30 composed of a material such as fused quartz rests upon a layer of a film of an acoustic bonding agent 14 which acoustically bonds block 30 to block 15. A thin film 31 of an electrically resistant material is coated upon block 30. Electrical leads 34 and film 31 are connected together at connecting means formed as beads 32 and 33, although connection terminals, pads or leads can be used. A clamping block 112 is acoustically bonded by a film bonding agent 114 to film 31. When a substantial current pulse passes through film 31, the termal energy produced launches an acoustic wave through thermoelastic expansion as explained above in connection with the systems described above. A film of 2000Å of Mo can be used for film 31 and a voltage of about 100 volts can be employed to produce about 200 watts in a 50 ohm device.

Figure 8 shows a thermal energy-to-acoustic transducer. A pulse generator supplies electrical current to a thin film strip of a conductor 50 which can be about 2000Å thick and composed of molybdenum. A plate 212 is composed preferably of single crystal Al_2O_3 0.05 cm thick and serves as a clamp for another thin film strip 131 of 2000Å thick Mo on its lower surface which is adapted to be heated by heat waves transmitted through plate 212 from strip 50 to strip 131. Strip 131 is acoustically clamped by plate 212 to material 15 bonded by acoustic bonding agent 14. Thus, strip 131 launches acoustic waves into material 15. This system can be operated at low temperature, e.g. the boiling point of liquid helium.

Figure 9 shows a source of a pulsed helium ion beam 109 in an evacuated chamber 90. A beam of helium ions 110 is directed through carbon clamping plate 312 to be absorbed by gold absorber layer 231. Layer 231 is preferably deposited upon the lower surface of plate 312. The sample 15 is similar to other samples described above and is connected to piezoelectric transducer 16. Acoustic bonding agent 14 is applied as usual.

Figure 10 shows a pulsed X-ray source 209 directing an X-ray beam 210 through a clamping layer 412 preferably of perylene 10-100μ thick deposited upon a film 331 about 200Å thick composed of Fe. Film 331 is deposited upon glass plate 330 bonded by acoustic bonding agent 14 to sample 15. A sensor 16 is included. The source of X-rays 209 uses pulsed X-rays from a material having a higher Z (atomic number) than absorber layer 331. Thus, the X-rays may be Kα X-rays emanating from a copper target when absorber layer 331 is composed of iron which has a lower Z than copper.

Note that energy could be directed through sample 15 in Figure 1A, etc. instead of the clamping medium 12 if sample 15 is transparent to the energy.

WHAT WE CLAIM IS:-

1. A pulse generator comprising a body having or being acoustically coupled to an energy absorbing layer, an energy source operable so to direct pulses of non-mechanical energy into the energy absorbing layer as to subject the energy absorbing layer to mechanical vibration which propagates into the body, and a vibration limiting medium acoustically coupled to the energy absorbing layer in a direction opposite the propagation of vibration into the body whereby the vibration limiting medium enhances the propagation of vibration into the body.

2. A pulse generator according to claim 1 in which the vibration limiting medium is a member bonded by a bonding agent to the said body.

3. A pulse generator according to claim 1 in which the body is acoustically coupled to an energy absorbing layer and the coupling between the body, energy absorbing layer and vibration limiting medium is achieved by at least one layer of a bonding agent.

4. A pulse generator as claimed in claim 2 or 3 in which said bonding agent is a viscous liquid.

5. A pulse generator as claimed in claim 2, 3 or 4, in which said bonding agent is propylene glycol.

6. A pulse generator as claimed in any preceding claim in which said vibration limiting medium is a member onto which the energy absorbing layer is coated directly.

7. A pulse generator as claimed in any preceding claim in which energy absorbing layer is coated directly on said body.

8. A pulse generator as claimed in claim 6 or 7 in which said energisable layer is coated by an evaporation coating process.

9. A pulse generator as claimed in claim 6 or 7 in which said energy absorbing layer is coated by a plating process.

10. A pulse generator as claimed in any preceding claim in which said energy absorbing layer is composed of molybdenum tungsten, or chromium and said vibration limiting medium is composed of glass quartz or sapphire.

11. A pulse generator as claimed in any preceding claim in which said energy absorbing layer is composed of aluminium and said vibration limiting medium is a polyester plate.

12. A pulse generator as claimed in any preceding claim in which said energy absorbing layer is an electrically resistive layer provided with connection means such as terminals, pads, beads or leads.

13. A pulse generator as claimed in any preceding claim in which said energy absorbing layer is gold and said vibration limiting medium is carbon.

14. A pulse generator as claimed in any preceding claim in which said energy absorbing layer is iron and said vibration limiting medium is perylene.

15. A pulse generator as claimed in claim 10 or 11 including a laser for energising said energy absorbing layer with pulses of electromagnetic energy.

16. A pulse generator as claimed in claim 15 in which said laser is operable to direct said pulses to said energy absorbing layer via said vibration limiting medium.

17. A pulse generator as claimed in claim 12 including a pulsed voltage source connected to said connection means.

18. A pulse generator as claimed in claim 13 including a pulsed helium ion beam source for energising said gold layer via said carbon medium.

19. A pulse generator as claimed in claim 14 including a pulsed X-ray source for energising said iron layer via said perylene medium, the X-ray source generating X-rays from a material with a higher atomic number than the iron.

20. Sonic pulse generator substantially as described with reference to Figure 1A, 1B or 1C of the accompanying drawings.

21. Sonic pulse generator substantially as described with reference to Figure 3 of the accompanying drawings.

22. Sonic pulse generator substantially as described with reference to Figure 6 of the accompanying drawings.

23. Sonic pulse generator substantially as described with reference to Figure 7 of the accompanying drawings.

24. Sonic pulse generator substantially as described with reference to Figure 8 of the accompanying drawings.

25. Sonic pulse generator substantially as described with reference to Figure 9 of the accompanying drawings.

26. Sonic pulse generator substantially as described with reference to Figure 10 of the accompanying drawings.

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Agent for the Applicants

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6 SHEETS *This drawing is a reproduction of the Original on a reduced scale*
Sheet 1

FIG. 1A

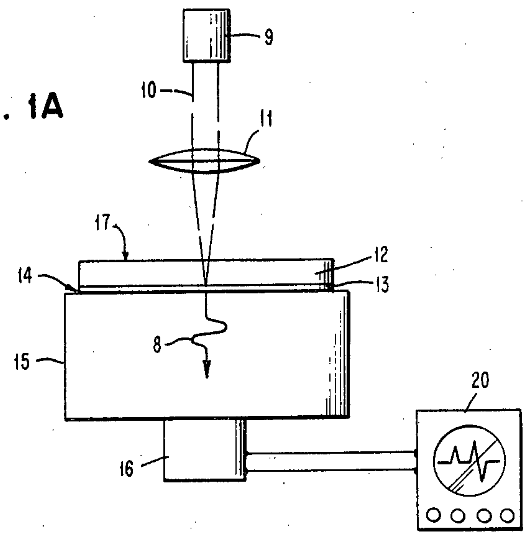


FIG. 1B

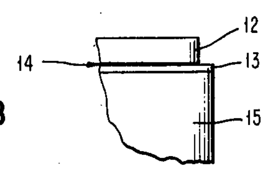


FIG. 1C

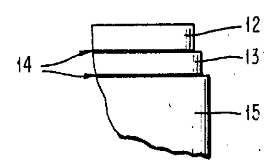


FIG. 2

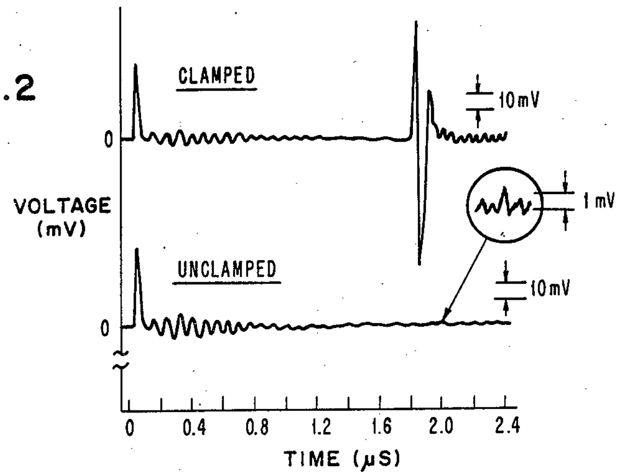

CLAMPED
UNCLAMPED
0
0
10mV
1 mV
10mV
VOLTAGE (mV)
0
0.4
0.8
1.2
1.6
2.0
2.4
TIME (μS)

FIG. 3

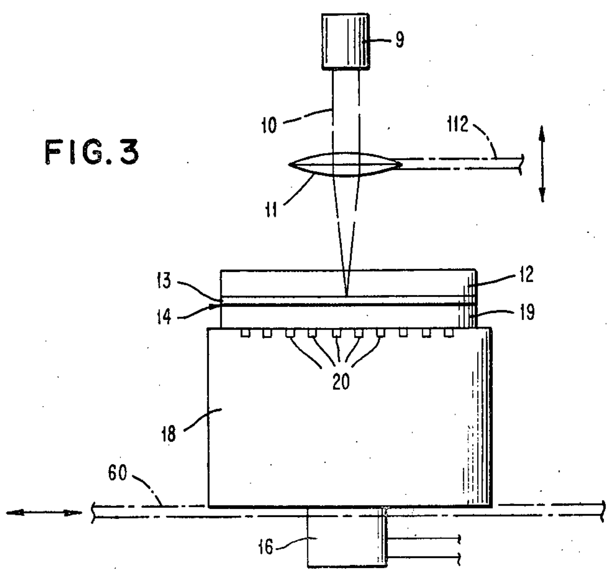

9
10
112
11
13
14
12
19
20
18
60
16

FIG. 4

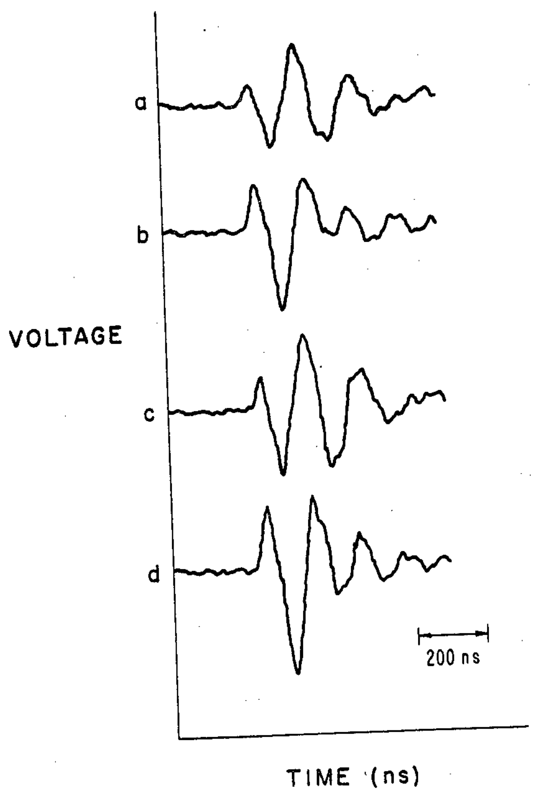


FIG. 5

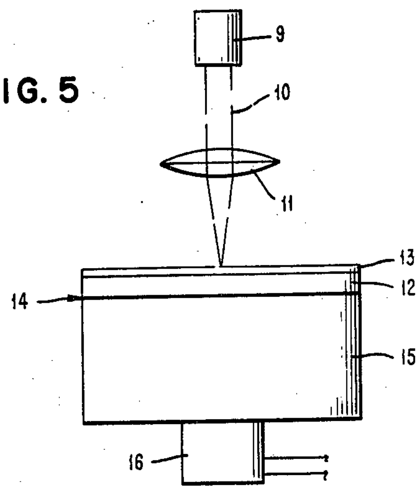


FIG. 6

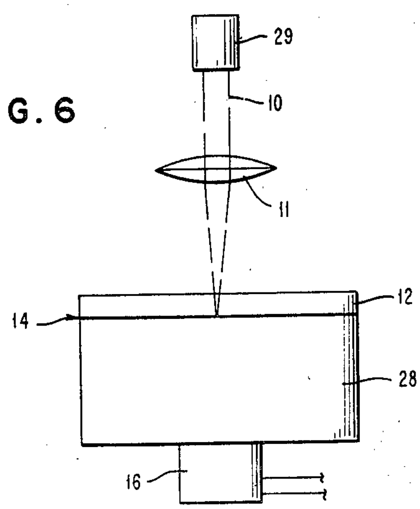
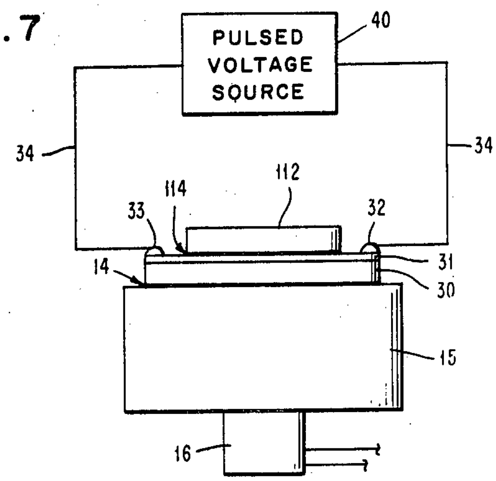


FIG. 7


PULSED
VOLTAGE
SOURCE
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34
34
112
114
33
32
31
14
30
15
16

FIG. 8

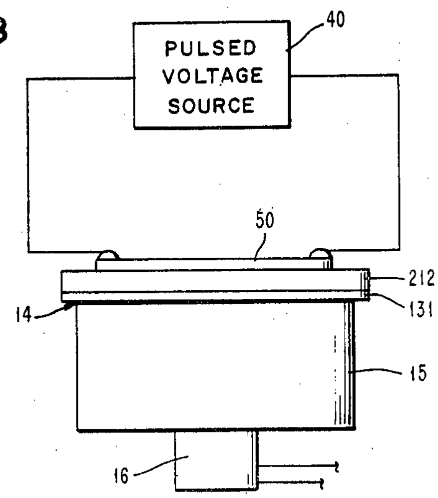

PULSED
VOLTAGE
SOURCE
40
50
212
131
14
15
16

FIG. 9

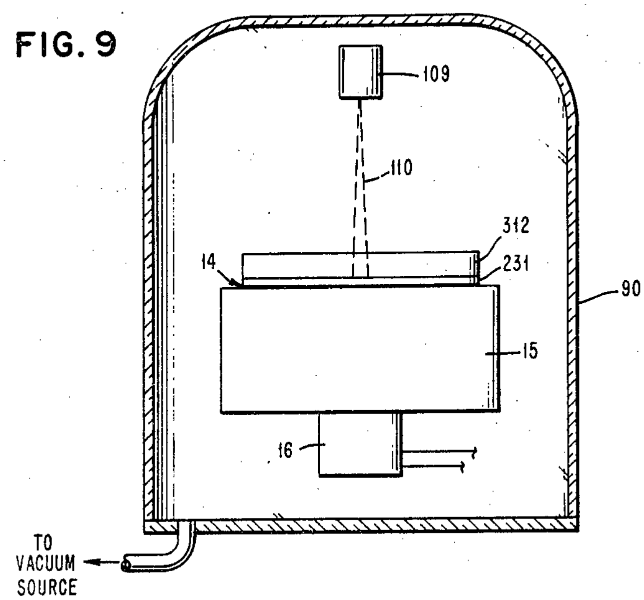
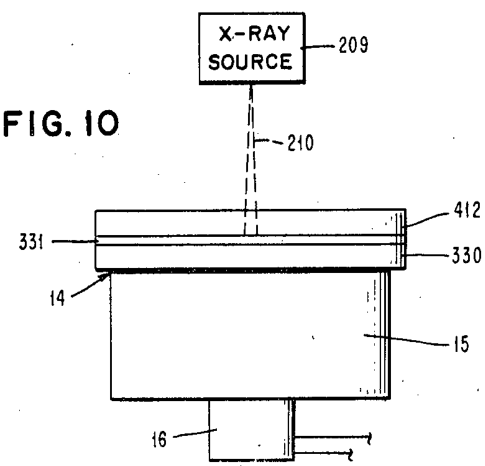

109
110
312
14
231
90
15
16
TO
VACUUM
SOURCE

FIG. 10


X-RAY
SOURCE
209
210
412
331
330
14
15
16