Dense Plasma Focus radiation source for microlithography & micro-machining

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ABSTRACT

We use a Dense Plasma Focus (DPF) device NX2, with improved insulator, electrode, and switching configuration, and with Argon filling to concentrate the main part of its radiation near 4 Å. In this case it can be used as a source for different aims in micro-lithography. One evident goal here is to increase spatial resolution of the method with the help of a source having a shorter wavelength in comparison with widely used Ne gas filling of DPF. But in particular it can be implemented in micro machining when it emits enough harder X-rays with Argon as a working gas, but it is attainable if plasma can reach $T_{pl} \geq 1$ keV at the pinching phase.

There are at least three possible ways to get the above temperature and high X-ray yield around wavelength of 4 Å. One is to use a mixture of light gas (ultimately deuterium) with argon to produce hot spots by plasma necking. Another one is to increase CS velocity in pure argon. The third one is to use a mixture of heavy gas (e.g. krypton) with argon to produce separation of gases at the shock wave front of a DPF current sheath and subsequently to compress argon by a "heavy shell". In the last two cases longer electrodes and lower initial pressure are needed for DPF-bank matching.

Using a pinhole with a CCD matrix and a pair of folded by different foils pin diodes in all three methods we have successfully reached a reasonable yield in the above-mentioned spectral range. It was respectively about 0.4J, 1.0 J and 10.0 J. Within all three modes of the DPF operation it was possible clearly to find a distinction between three characteristic regimes: a pinch regime, a hotspot regime, and a runaway regime.

Keywords: X-ray source, micro-machining, Dense Plasma Focus, Ar-gas filling, pinch, hot spots, heavy shell compression

1. INTRODUCTION

It is well known that the shorter wavelength emitted by an X-ray source the better resolution can be ensured at the proximity X-ray lithographic process. It is so mainly because of lesser diffraction of the radiation on the mask. But the limit for the wavelength from the more energetic side of spectrum is implied by a photoelectron production within a resist and by increasing transparency of the mask. This limit lies near 3...5 Å. A majority of the DPF based X-ray sources use a Ne gas filling of the device, thus providing an X-ray luminescence in the vicinity of 12 Å. So there is enough room to find a possibility to decrease the wavelength for the above-mentioned goal. But there is another important application where this short wavelength can be useful.

During the last two decades of rapid change in technology, engineers and physicists realized the tremendous potential of using lithographic, etching and other micro-fabrication tools developed for integrated circuit manufacturing to make mechanical rather than electronic structure (e.g. see [1]). In the late 1950's, for example, mechanical strain gauges were fabricated from silicon wafers and physically glued onto large mechanical components to create a pressure sensor. Although these sensors were expensive because of the hand assembly operations, they were quickly adopted for several critical aerospace and industrial applications because of their small size and superior performance.

As the technology progressed, more and more mechanical functions of the sensors were incorporated into the silicon chip, including the deformable diaphragm, the diaphragm support frame, wire bonding pads, and a stress-isolation "constraint" structure that protected the pressure sensing diaphragm from extraneous packaging stresses. These features were built in chips by using the same parallel processing, mass production techniques, which have already made the integrated circuits so cost effective.

With most of the mechanical and electronic elements of a pressure sensor integrated on a single mass-produced chip, it became possible to use micro-mechanical sensors in two high volume applications [2]. In the early 1980's, the automotive industry began manufacturing manifold absolute pressure sensors for the newly mandated emission control systems, which soon became indispensable for automotive pollution control.

At the same time, silicon micro-machined pressure sensors began replacing reusable blood pressure instruments in the operating room. Earlier models of blood pressure sensors were costly and delicate, and they required expensive sterilization between uses. Because the silicon chips could now be manufactured inexpensively and in high volume, the sensor could be thrown away instead of being sterilized and re-used, thereby minimizing the possibility of infection. Therefore, there is a great demand of micro-machined disposable blood pressure sensors these days.

These two successful market application alone have transformed the micro-machining from a cottage technology to a healthy self sufficient, expanding industrial sector with enormous emerging applications.

Today, micro-machined structures are broadly referred to as micro electromechanical systems (MEMS). There are several standardized mechanical fabrication methods available, some of which can be used to achieve small dimensional features. These include subtractive processes that selectively remove material from a piece of stock to form the desired geometry and numerous molding procedures to form structures. Subtractive processes include mechanical (cutting, grinding, shaping), and optical (laser etching) methods. The basic concept is to sequentially superimpose two-dimensional pattern on to wafers, with each pattern representing a step of deposition or etching of the deposited layer or substrate itself. There are three basic steps (deposition, photo-resist pattering and etching) repeated until the entire fabrication sequence is completed.

The photo-resist patterning process executed with a help of lasers with a wavelength of the close ultra violet range can be substituted by either a very soft X-ray (~10 nm) projection microlithography or by a relatively harder X-ray (~1 nm) proximity one. However in the last case a very short wavelength radiated by an X-ray source can be explored in micro machining not for the aim of a nano-scale structure fabrication as it is in nano-lithography. It will be implemented here because of the deeper penetration depth of its radiation inside the resist thus providing a possibility to form within the resist's volume a three dimensional structure. Within the candidates for the appropriate X-ray source a Dense Plasma Focus device looks very promising because of its low cost and now available high rep rate and high efficiency of it [3]. Its construction gives a possibility to operate with an X-ray beam directed at any angle to the resist layer (even adjustable during the operation).

2. APPARATUS AND DIAGNOSTICS

We use a Dense Plasma Focus (DPF) device NX2 [3], with improved insulator, electrode, and switching configuration (Fig. 1), and with Argon filling to concentrate the main part of its radiation near 4 Å. NX2 is a pinch plasma source proved to be suitable for X-ray lithography when neon is used as a working gas. In that case a current sheath (CS) velocity below 10^7 cm/s, plasma temperature T_{pl} of 300 eV and radiation yield of 10-15 Joules of soft X-ray - in the wavelength of 8-12 Å - were observed. It can also be used as a source for some other aims in microlithography. In particular it can be implemented in micro-machining but only when it emits enough harder X-rays with Argon as a working gas, and if this argon plasma can reach $T_{pl} \sim 1$ keV. In pursuing these goals our modifications of the apparatus were as follows.

1) In comparison with our previous experiments we have changed a configuration of the anode by introducing a tube-like Pyrex insulator around the anode thus making the whole DPF electrode geometry to be more close to the classical Mather type one

2) We have substituted a rail-gun switches for a pseudo spark gaps to increase the operational life-time of these systems and to decrease a jitter of our 4 switches

3) We have re-designed our gas filling system making possible with it to prepare a composite gas mixtures of different gases with various partial and total pressures

During its dynamics at the end of the rundown phase of plasma current sheath (CS) in DPF goes sequentially through the following stages:

- a stage of a shock wave implosion and reflection at an axis of the device chamber,
- a stage of a pinch formation and its confinement near the axis, and

- a phase of a development of the Raleigh-Taylor instability (flute instability, i.e. local plasma necking),

which are usually proceeded as radiation stimulated processes.

At least three possible ways are conceivable to get the above temperature and high X-ray output in the wavelengths around 4 Å. One is to use a mixture of light gas (ultimately deuterium) with argon to produce hot spots by necking in composite plasma. In this case it is not important which value of the CS velocity has been before the collapse - all processes taking place after the so called "first compression" are relatively independent on the rundown phase and ruled mainly by plasma viscosity, resistivity and radiation processes. Another one is to increase CS velocity in pure argon. In this case because the final temperature of a pinch is formed by a conversion of the translational energy (work) of the CS into heat we may reach desired parameters indeed. The third one is to use a mixture of heavy gas (e.g. krypton) with argon. In this case because a shock wave (SW) produces heating of plasma mixture up to the same temperature for both substances, we shall have at the shock front the two types of ions with the same temperature but with different ion velocities (because of difference in their masses). Thus finally we produce a separation of gases at the shock wave front having lighter gas (Ar) in front of the SW and heavier gas (impoverished mixture) at the rear side of it. Subsequently at the SW collapse at Z-axis we compress argon arriving first to the axis by a "heavy shell". In the last two cases longer electrodes are needed for DPF-bank matching.

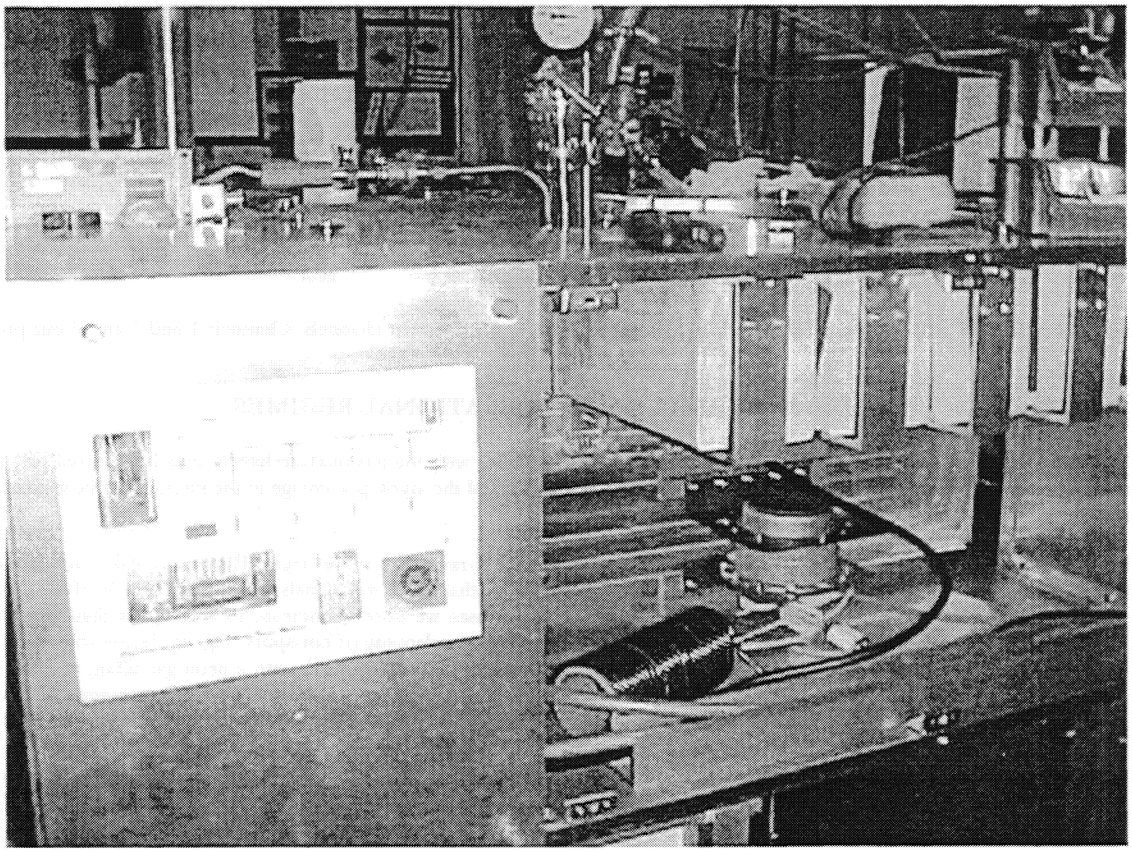


Fig 1: Modified NX2 facility with a pseudo spark gap switch at the front in the lower part of the photo.

To observe the regimes of the DPF operation we use several diagnostics: a Rogowski coil, a five-channel diode X-ray spectrometer [4], and a pinhole camera with image recording by a CCD matrix, both positioned end-on (along the Z-axis).

BPX65 PIN detectors was chosen for our X-ray output spectral and absolute measurements. The glass window is removed and diodes are folded in different foils. The overall sensitivity curves of the filter diode combinations as a function of wavelength is shown in Fig. 2. Sensitivity is given in C/J, wavelength - in Å. Specifically we use mainly for our goals the diodes No 1 and No 2. As it is seen from the curves namely this pair can give us a reliable information on the X-ray intensity in the region near 4 Å. If the ratio between signals from these detectors (of the 2nd channel to the 1st one) will be 2 to 4, it will mean that the main part of X-ray radiation concentrated namely near the wavelengths of resonance lines of H-like and He-like argon [5]. If the ratio will be bigger than this, it will mean that our plasma is cooler, and no appreciable amount of it was heated till ~1 keV. Contrary to this if the ratio will be close to 1, it will be a clear evidence that the main part of X-rays would be a result of an interaction with an anode of very high energy electrons generated during a so called "runaway" process.

In a pin-hole camera we use a diaphragm of the 50 μm diameter for a visualization of the X-ray sources and to make a distinction between hot spots (expected to have a size less than 50 μm) and a pinch (should be bigger than 50μm).

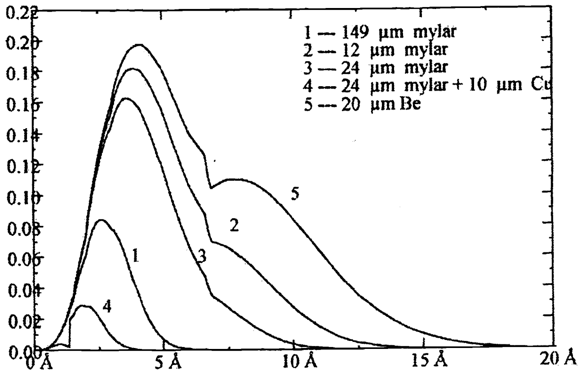


Fig 2: BPX 65 PIN sensitivity combined with foil absorption curves for different channels. Channels 1 and 2 are of our prime use.

3. DENSE PLASMA FOCUS OPERATIONAL REGIMES

Working with a mixture of deuterium and argon we filled our chamber with the gas mixture having initial optimized pressure around 4 mbar. We change this pressure within the limits 1 to 9 mbar, and the argon percentage in the mixture has been changed from 2% till 40%. Anode length in these experiments was 5 cm.

Using this first method the following observations were made. Usually X-ray pulses in this regime had many spikes and lasts for a relatively long period of time - about 100 ns (see Fig. 3). We observe that the X-ray signals from two channels of pin-diodes folded with different foils have various "saturation" levels. In some cases we observe increase in area rather than amplitude before the amplitude reaches the "saturation" level as we believe in some overlapping of hot-spots (Fig. 4). Before with the same diodes but with lower energy X-rays having shorter penetration depth in the diode (~12 Å with a neon gas filling of DPF) we observe amplitudes almost 5 times higher than the present ones. And according to our experience a real saturation of diodes starts to take place from about 5-7 volts. So in this case we have measured the real amplitude evolution of the X-ray signals. This rather complicated waveform of the pulses resulted from a formation of many hot spots positioned nearby Z-axis of the DPF chamber. But at the same time because of this nontrivial shape of the pulses the overall X-ray yield should be calculated with taking into consideration the real area under the X-ray pulse.

When we compare a number of hot spots and X-ray yield Vs percentage of argon we observe a kind of U and inverse U shapes respectively (Fig. 5,6). They have minimum at around 20 percent of argon gas for the number of hot spots and a maximum at the same point for the yield. It means that the highest yield is produced not by a multiple hot spot formation, but by a relatively stronger compression in a few of them.

Following to the X-ray output graph with respect to percentage of argon gas "up and down" (under its increase and decrease) we observe also a hysteresis type curve (Fig. 6). This phenomenon can be explained on the basis that the ion current component was fed with a gas absorbed by the anode in previous shots.

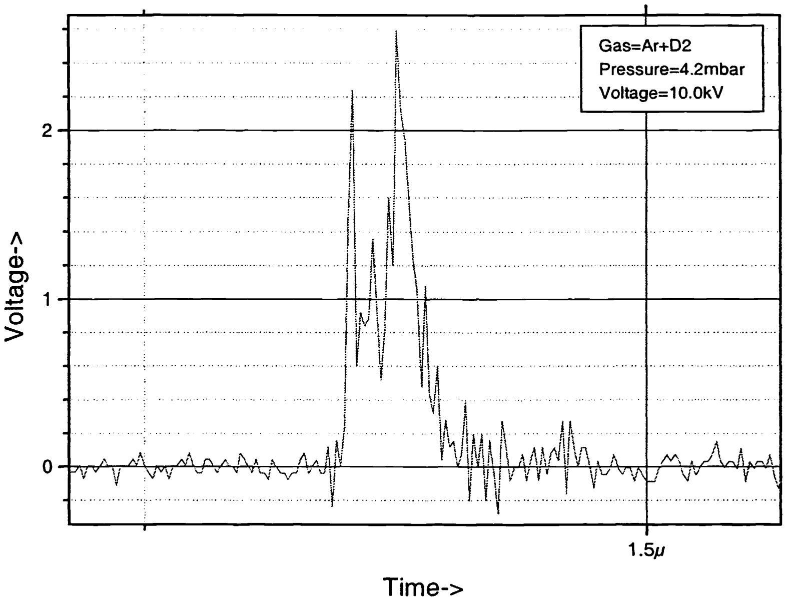


Fig 3: Amplitude Vs time at the X-ray output curve from Channel 1.

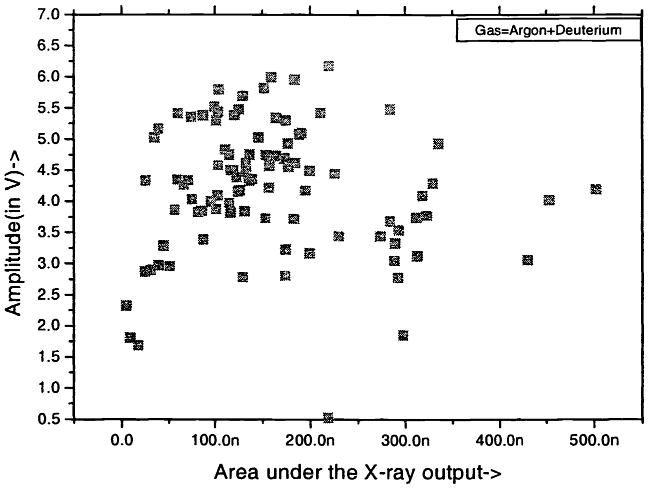


Fig. 4: Amplitude Vs Area under the X-ray pulse curve from channel 2

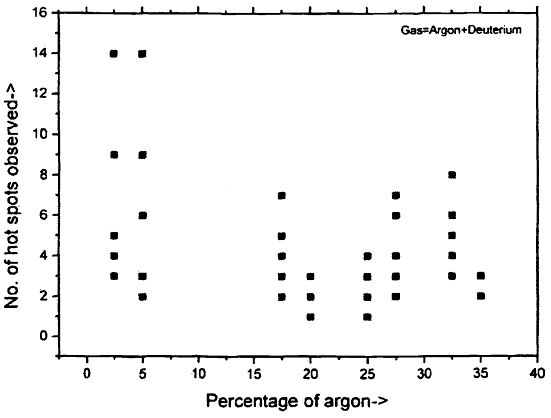


Fig 5: Graph between the number of hot spots observed and percentage of Argon content.

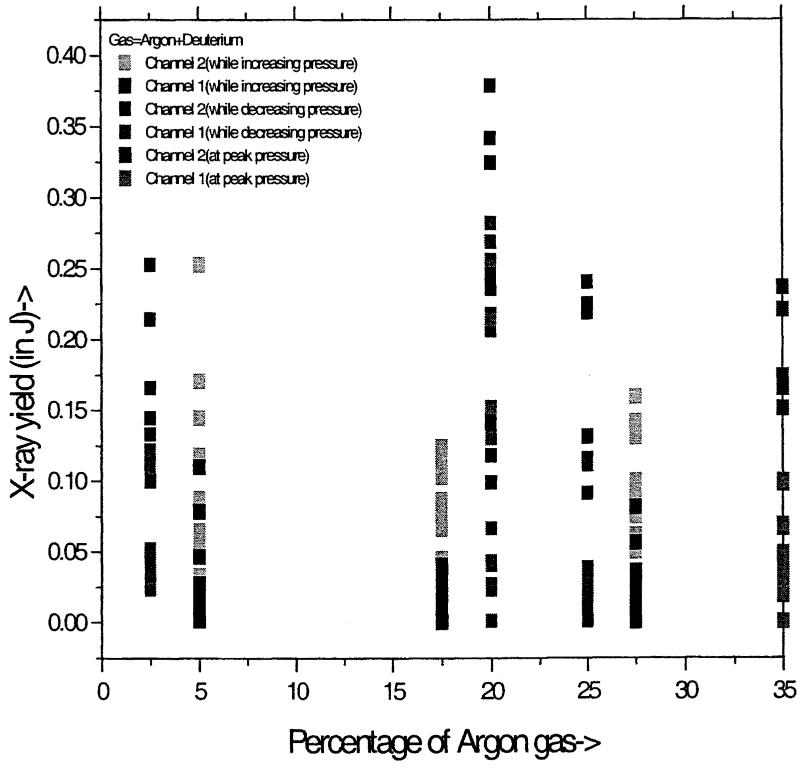


Fig 6: Graph between X-ray output Vs percentage of Argon admixture.

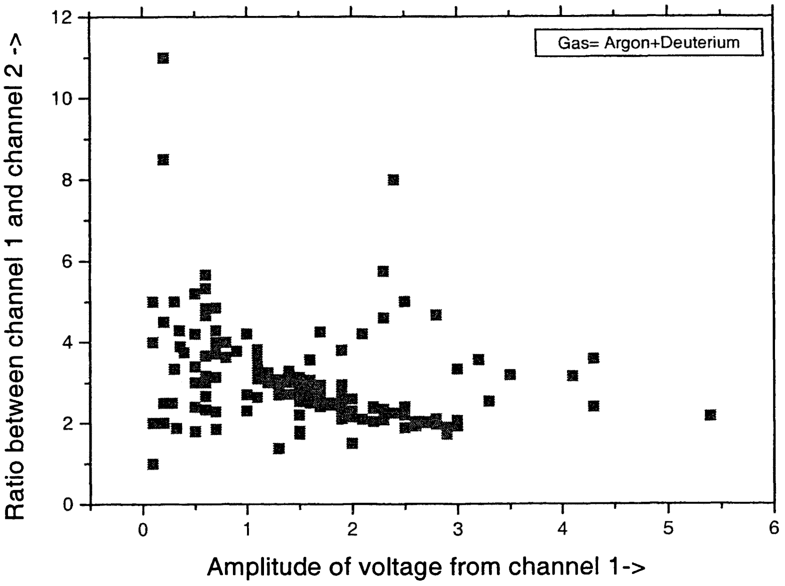


Fig 7: Graph between ratio of the two readings of voltage (channels 1 and 2) Vs amplitude from a lower voltage channel.

We found a ratio of areas as well as the ratio of the amplitudes of the two X-ray detection channel signals (in each shot and as an average) almost in all shots to be equal to 2 to 4. Exceptions seen in Fig. 7 are mainly belong to the conditioning set of shots. So, the main part of radiation at the hot spot formation regime is concentrated near 3...4 Å. The best value of its intensity reached was about 0.4 J, and all successful shots (after a conditioning set of about 100 shots it became quite reproducible) are concentrated between 0.2 and o.4J. In order to increase this X-ray yield with the hot-spot mechanism new regimes using either many hot-spots formation at the same time or lesser number hot-spots leading to higher compression, higher density and higher temperature should be found.

Thus, for the DPF operating with the short anode we have found the possibility to increase its X-ray yield at 3...4 Å to an appreciable value by using a mixture of D_2 + Ar and exploring a flute instability as a heating mechanism.

In second regime - operation with pure Ar (as in the third one) - we use a longer anode having a length of 8 cm. The two-step idea was to increase the CS speed well above 10^7 cm/s, what demands at the same time decreasing a filling gas pressure and (to match the electrical characteristics of the circuit with the moving CS) increasing the electrode length. For conditioning of the chamber with the new electrode it was done more than 100 shots with different pressures of Ar and with pumping out the system after every 10 shots. We have found an optimal pressure in the region 0.6...0.9 mbar.

In this regime we have made the following observations. Depending on the initial pressure it was found two regimes of the DPF operation - with a single pinch and with a multiple hot spot formation (Fig. 8). Diameter of the pinch appears to be of ~100 μm whereas different hot spots has equal diameter of the order 50 mμ, which means that its real dimensions are much smaller.

Shape of the X-ray pulse in case of a hot spot regime was about the same as in Fig. 3, whereas in a pinch regime in became much shorter - about 30 ns - with a smooth and symmetrical, "bell-like" contour.

At the best shots the X-ray output reached a little more than 1.0 J whereas the data on all successful shots has been concentrated between 0.3 and 1.0 J. The ratio of signals from above two channels mainly was concentrated between 2 and 4 confirming the reached main goal. But sometimes under the attempts to accelerate the CS up to higher velocities by pressure decreasing we have found that the X-ray yield in both channels became equal (ratio about 1) without parallel increasing in its amplitude. We connect this fact with the runaway processes in the DPF as it was mentioned above.

So by this experiment we have found a way to increase X-ray yield at the region of 3 to 4 Å in a certain extent for DPF, operating with pure Ar, by implementing a longer anode.

In third regime (appeared to be lesser stable) we have made the following observation.

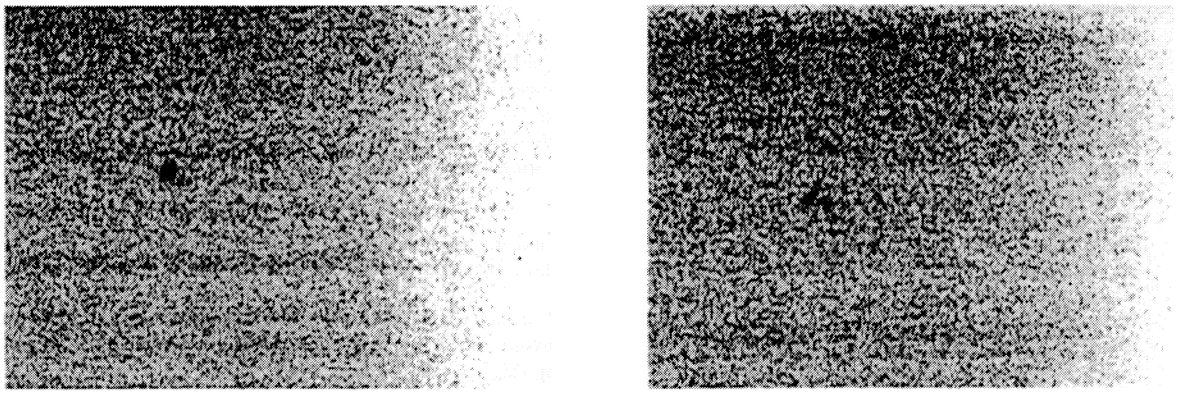
We use a mixture of Ar and Kr in the proportion of 50:50. Optimal pressure was found about the same as in a previous case, yet with it we had a problem. Namely during a sequence of shots we had a permanent increasing of the pressure inside the chamber. It demands to pump out the DPF chamber a little from shot to shot. Because of this procedure the final relative percentage of a mixture became a bit uncertain.

We have found in this mode of the DPF operation all three types of plasma dynamics - pinch regime, hot spot regime and runaways. The most interesting was the first one, which demonstrated a ratio of signal in the same range - 2 to 4. But we have found here at the same time two remarkable things.

At first, the shape of the pulse was completely different. It has a very short rise time (equal to the oscilloscope temporal resolution) and a relatively slow decreasing tail. It was smooth without any spikes as it was in the Fig. 3. Pulse duration sometimes had reached more than 100 ns. We believe that this type of the X-ray pulse is in favor of the hypothesis that we have reached a regime with a compression of a working gas by a "heavy shell".

At second, amplitude of this pulse was well above 10 V, and the best our shots have shown the yield on the level of 10 J and more. All successful shots had an output concentrated within the range of 1...10 J.

So by this experiment we have demonstrated that working with a mixture of two gases with strongly different masses of their atoms we can reach a formidable separation of them at the shock front thus providing conditions for subsequent compression of lighter gas (Ar) by a heavy shell (Kr). In this way of Ar plasma compression and heating we have reached the yield in the region of 3 to 4 Å as high as 10 J with the device operating at an energy level of about 2 kJ.



a) b)

Fig. 8: Two regimes with a pure argon gas filling - pinch regime (a) and hot spot regime (b)

Summarizing our results we may state that by this set of experiments we have shown in principle a possibility to reach with NX2 the efficiency in the region 3...4 Å of the same order what we had with this device for a neon filling gas (8...12 Å X-rays). But with those regime of this facility we made several successful exposures of resists with a 100-nm structure for several hundred shots. Such a big number of shots is necessary because of a relatively big difference in the X-ray output of the device. But it is not dangerous. Indeed, with a rep rat of 15 Hz and with a possibility to interrupt the exposure of a resist at any time just following to the dosimeter readings it is possible to satisfy the demands of a microlithography or micromachining processing. At the same time it will be interesting to verify the investigated possibilities with our another device - NX1, which has demonstrated the efficiency of X-ray generation with a neon filling an order of magnitude higher [3].

4. ACKNOWLEDGEMENTS

The authors would like to thank Mr. Oon How Tan, National Institute of Education, NTU, for a help in conduction the experiments.

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