Chapter 1 Introduction

1.1 Introduction and Motivation

International Technology Roadmap for Semiconductors (ITRS) stated that the Extreme Ultraviolet Lithography (EUVL) using 13.5 nm wavelength being the most promising technology for Next-Generation Lithography (NGL) introduced to High-Volume Manufacturing (HVM) [ITRS 2009] beyond the 22 nm half-pitch patterning in the semiconductor industry in the near future. SEMATECH (SEmiconductor MAnufacturing TECHnology) reported various optical components for the EUVL which are at good status but there still remain three main roadblocks, which are the EUV source, the resist and the mask [Int. Symp. EUVL (2008), Wurm (2009)].

EUVL by using light source of 13.5 nm EUV with up to 180 W at intermediate focus (IF) in a bandwidth of 2 eV is the next milestone of semiconductor industries [Int. Symp. EUVL (2008)]. Intense EUV source is the main concern for the realization of the EUVL. From the year 1996 to 2008 cumulative investment on EUV source research and development reached over USD 100 Million. Hence this work is much motivated by the demand of an intense EUV source by the semiconductor industries, whereby plasma technology is one of the solutions.

Solution to the intense EUV light source includes Gas Discharge Produced Plasma (GDPP) or Laser Produced Plasma (LPP), where intense pulsed EUV radiation can be produced. Another candidate of course is the synchrotron light source. LPP is the more practical approach which allows operation at high repetition rate with controllable thermal load at the required high power laser. However, the LPP system requires a high cost of setup and maintenance of the high power laser. For GDPP based EUV source, it has several advantages as compared to the immense, complex and high cost of ownership (CoO) synchrotron. Hence, it is premature to validate which type of EUV production will be suitable for the industries. Several types of gas discharges, which include hollow cathode discharge, capillary discharge, Z-pinch and plasma focus have been studied by many researchers. Plasma focus discharge is believed to be one of the GDPP systems capable of producing pulsed EUV emission for EUVL [Fomenkov et al. (2004) 168, Fomenkov et al. (2004) 3266]. It is also simple in design, compact in dimension and low maintenance cost.

Dense Plasma Focus (DPF) device can produce, by electromagnetic acceleration and compression, short-lived plasma that is hot and dense such that it becomes a copious multi-radiation source such as hard and soft X-rays, ultraviolet, extreme ultraviolet (EUV) [Favre et al. (1992), Moo et al. (1995), Fomenkov et al. (2004), Raspa et al. (2007)] and particle beams including ion beam and electron beam [Schneider et al. (1985), Takao et al. (2003)].

Most of the DPF devices investigated are of several kilojoules to 1 mega joules in electrical input energy [Aliaga-Rossel et al. (1998), Gribkov et al. (2002), Schmidt et al. (2002)]. The Asian African Association for Plasma Training (AAAPT) established in 1982 has carried out a lots of joint research work based on the 3 kilo joules plasma focus facility, called the United Nations University/International Center for Theoretical Physics Plasma Fusion Facility (UNU/ICTP PFF) [Lee et al. (1988), Yap et al. (2005), Mohammadi et al. (2007)].

In recent years, much efforts is made to either improve the energy density of the plasma for fusion product [Lee (2009) 151503, Kubes et al. (2010)] or enhance the portable and low energy designed system as radiation source [Silva et al. (2001), Moreno et al. (2003), Fomenkov et al. (2004)]. Several research groups have reported development of a portable plasma focus devices with energy only in the range of tens to hundreds of joules operating at high frequency [Lee et al. (1998), Fomenkov et al. (2004) 168].

Some of the Mather-type plasma focus devices with different input energy and anode diameter are listed in Table 1.1. These devices have similar plasma energy density parameter and drive parameter in the same order of (1 - 10) × 10^{10} Jm^{-3} and 77 ± 7 kA/ cm $mbar^{1/2}$, respectively. [Lee et al. (1996)]. The conceptualization of any electrical input energy for a plasma focus can be made based on the fact that the plasma energy density parameter $28E/a^3$ and the drive parameter $I_o/ap^{1/2}$ (where the E, a, I_o, p are input energy, anode radius, peak current and operating pressure, respectively) are practically constant in a wide energy range.

Table 1.1 Mather-type plasma focus devices with different input energy.

DPF Device	Input Energy (kJ)	Anode Diameter (cm)
PF-1000	1000	23
SPEED 2	187	11
ENEA PF	6	8
UNU/ICTP PFF	3	1.9
NX 1	3	3
NX 2	1.9	4
PF 400	0.176 – 0.539	0.6
TANDIL (Nano Focus)	0.125	1.5
Miniature PF Machine	0.058 – 0.160	0.95
PF 50J CCHEN	0.05 – 0.07	0.6
NF (Nanofocus)	0.0001	0.042

Other characteristics of the plasma produced by optimized plasma focus devices regardless of the input energy include electron density of the plasma (10^{25} m^{-3}) [Silva et al. (2002)], electron temperature (200 eV - 3keV) [Mather (1965), Asif et al. (2004)], ion temperature (300 eV - 1.5 keV) [Forrest et al. (1974)], axial velocity of current sheath (10^5 cm/μs) [Al-Hawat (2004)] and its radial velocity (10^5 cm/μs) [Silva et al. (2001), Moreno et al. (2003)]. However, with a low input energy, the plasma volume produced is less, hence less amount of radiation compared to those device try using high input energy.

Pulsed radiations generated from a low energy plasma focus device are investigated here. Application of the plasma focus radiation source can then be explored. Some of the work related to applications are nanolithography in microelectronics which make use of the intense EUV or X-ray [Bogolyubov et al. (1998), Banine et al. (2004)], the pinch plasma as UV and X-ray source [Lee et al. (1998)] and as EUV light source for extreme ultraviolet lithography (EUVL) [Fomenkov et al. (2004) 168, Fomenkov et al. (2004) 3266].

1.2 Literature Review of the Plasma Focus

Plasma focus research can be dated back to early 60's where the device has been developed and efforts were concentrated on improving its performance as a thermonuclear fusion facility. It was observed in the early study that the dense plasma focus discharge has produced neutron output of more than 10^{10} neutrons per shot, typically lasting about 100 ns by using deuterium.

A research team at the Kurchatov Institute in USSR, Russia led by Filippov proposed a modification to the linear Z-pinch by providing an inversed pinch phase as a pre-pinch phase and form the Filippov type plasma focus [Filippov et al. (1962)]. This pre-pinch phase provides preliminary heating of the plasma before the radial pinching action occurs. Mather and his team at the Los Alamos National Laboratory in USA also proposed a similar concept [Mather (1964), Mather (1965)].

Filippov type plasma focus has the cathode forms an outer electrode that encloses the inner anode. The inner electrode which is the anode is completely insulated and the plasma will be formed between the end of the electrode and the wall of the chamber. This design has made it difficult to diagnose the plasma as it is completely blocked by the electrodes.

Mather type plasma focus has the electrodes arranged in a cylindrical configuration like a coaxial plasma gun. The outer electrode is the cathode, which can be either a cylindrical wall or a set of rods surrounding the anode. The plasma will be formed at the open end of electrodes, allowing end-on diagnostic. Diagnostics from the side-on view can also be arranged in between the gap of the rods forming the cathode.

The plasma pinch produced by these two types of plasma focus appears to be similar. The main difference between these two types of configuration is the aspect ratio, which is the ratio of the electrode length to the inner electrode diameter. The Filippov type configuration has a aspect ratio of less than 1, typically about 0.2. However, in the Mather type configuration this is much bigger than 1, typically about 5 to 10. Figure 1.1 illustrates the electrode geometries of the Mather type plasma focus and Filippov type plasma focus. In this current project, Mather type configuration is employed.

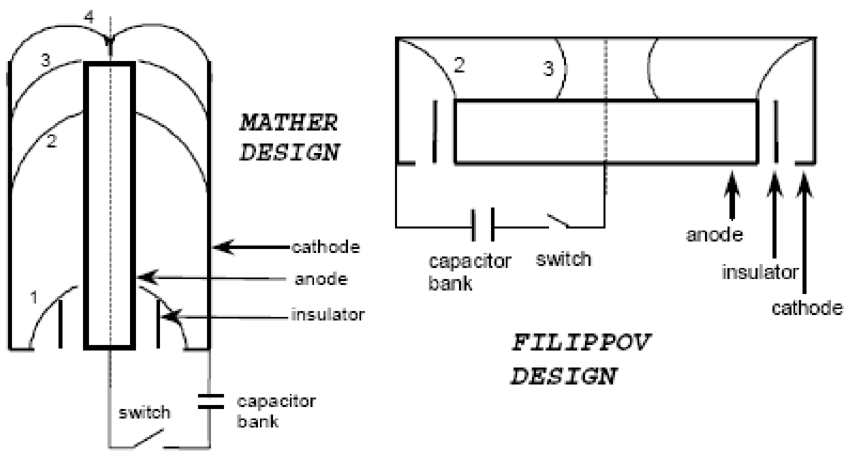

Figure 1.1 Schematic drawings of Mather and Filippov type dense plasma focus devices (DPF) [Fillippov et al. (1962), Mather (1964)].

In 1965 Mather [Mather (1965)] investigated a plasma focus with particle density around 2 - 3 × 10^{19}/cm^3, plasma temperature in the order of several keV, plasma life-time approximately 200 ns and intense neutron yield of more than 10^{10} per burst. From the soft X-ray pinhole camera, Mather observed two overlapping or separated plasma pinch in a single discharge and the large X-ray intensity was correlated with the large neutron yield. From the measurement of radial distribution of magnetic field, he observed the non-planar current sheath moving with velocity of about 10 cm/µs along the electrodes in the axial acceleration phase.

Lee et al. [Lee et al. (1972)] attempted to use Pyrex instead of copper as the outer cylinder for optical access to the pre-focus region and found that not all the current moves down the tube with the main current sheath at first half cycle. But the remaining current forms the second current sheath moving out from the backwall at the start of current flow in the second half cycle. This effect is called the current shedding effect. He observed the current sheath moving behind the shock front with slightly lower axial velocity of 6.9 cm/μs in the focus tube.

The slow propagation speed of the current sheath at high operating pressure will lead to an inefficient and leaky piston [Kwek et al. (1990)]. Poor piston efficiency will lead to low rate of fusion reactions hence establishing a high pressure limit. On the other hand at low pressure operation, fast driving speed can be achieved but the current sheath will become thick and affect the specific heat ratio γ which determines the compressibility of the current sheath. Hence the pinch plasma will only occur at operating pressure regime where the average velocity of the current sheath is about 10 cm/μs.

The drive parameter is defined as the peak drive current per unit anode radius divided by the square root of the fill density, $S = \left(\frac{I_p}{a}\right) \Big/ \rho_o^{\frac{1}{2}}$ [Lee et al. (1996)]. The drive parameter, S of about 89 ± 8 (kA/cm)/torr$^{1/2}$ for deuterium, corresponds to a peak axial speed of just less than 10 cm/μs. The nearly constant value of the driven parameter implies the plasma temperature in each phase of the plasma dynamic should be the same over the energy range of plasma focus and hence the radiation yield will depend on the plasma volume and its lifetime. By using a simple dynamic model [Lee et al. (1996)], the linear dimension and the lifetime of the gross plasma focus pinch can be related to the anode radius. This observation can be applied to other gases such as argon, neon and xenon.

An effort to achieve yield enhancement by breaking the speed limit had been studied [Serban et al. (1997)]. In this experiment, the current sheath speed at the axial acceleration phase was raised up to 15 cm/μs and the drive parameter obtained is 120 (kA/cm)/ torr$^{1/2}$ by using tapered anodes. This higher speed of current sheath as the magnetic field pressure increases implied the achievement of higher temperatures and energy densities of the pinch column, hence leads to an enhanced radiation output.

In the dense plasma focus device, the homogeneity of the accelerated current sheath is an essential condition for a plasma focus with high energy density. When the breakdown process is investigated by imaging techniques [Donges et al. (1980)], it was found that depending on the operating pressure, filamentary discharge may be initialized along the insulator thus affecting the homogeneity of the current sheath. Filamentary discharges occurred randomly between the electrodes was also observed.

A novel approach of using knife-edge cathode at the bottom of the tube close to the insulator was proposed by Dongres et al. [Donges et al. (1980)]. With this setup a considerable reduction of the number of filaments and an enhancement of the optical intensity of the gliding discharge was observed. The plasma pinched at the lower limit of the operating pressure range was reached compared to the setup without the knife-edge. As was discussed at length elsewhere, the further investigation of the physical processes leading to the breakdown, the second breakdown formation and its influence on the dense pinch had also been reported [Krompholz et al. (1980), Bruzzone et al (1993)].

Deutsch et al. [Deutsch et al. (1983)] used a general theory, Taylor's relaxation theory, to simulate final structure of the plasma focus and confirmed by the experiment data from POSEIDON and NESSI [Nahrath (1978)]. In this study, the dissipative effect, the pressure and the kinetic energy were neglected. Thus, Deutsch observed a system of eddies superimposed on the reversed field pinch structure. The analysis results showed that the intensity and the structure of the eddies depend sensitively on the total current. The eddies dimensions were determined from the ratio of the compressed longitudinal filed to the azimuthal field of the current.

In 1988 Deutsch et al. [Deutsch et al. (1988)] continued the studies of the pinch dynamics of the plasma focus to explicate the ion acceleration mechanism. He proposed the ion gyro-reflection-acceleration mechanism in the simulation to manifest the non-thermal ion development as well as looking for experimental manifestations. Deutsch concluded that the pinch equilibrium and stability were essentially governed by fast ions. Thus classical MHD theory was inapplicable for equilibrium and stability investigations due to these plasmas deviated from a Maxwellian velocity distribution. Yet the author suggested using the kinetic theory or single particle motion to adequately explain the compressional pinch plasma.

By employing the pinhole imaging technique with different filters and Johann SiO_2 spectrograph, plasma pinches of 10 – 100 µm in size and the X-ray spectra of multicharged ions of the impurity for discharges in deuterium doped with xenon were observed [Koshelev et al. (1988)]. The brightest and smallest pinch was obtained with an impurity concentration of 1 - 2%, while increasing the impurity concentration to 8% or more will cause the plasma pinch to be destroyed. Thus, the presence of too much impurities will change the energy balance significantly in the plasma and hence the plasma focus pinching regime.

Interaction of the plasma with the target at various distances from the anode was studied by using shadowgraphy [Lee et al. (1990)]. Lee observed the post-focusing dynamic when a flat target placed just above the anode with distance less than 10 mm. Hence he suggested the possibility of sequential focusing as a result of the flat target [Lee (1991), Nisar et al. (1993), Gupta et al. (2000)]. He also noticed a significant drop in the neutron yield and postulated it to be due to the interaction of the target with a deuteron beam accelerated downstream out of the focus region.

Moo et al. [Moo et al. (1991)] employed a different approach to investigate the neutron emission. He used a metal target and a deuterated target positioned at different axial distances from the end of the anode of a plasma focus. The results showed significant neutron counts with the two different target, confirmed that the beam-target mechanism played a primary role and responsible for more than 85% of neutron production. The remaining 15% of the neutron yield was due to the thermonuclear reaction occurring in the pinched plasma. Similar result was also reported by Kelly [Kelly et al. (1996)].

Around the year 2000, attempts were made to check possibility of operating the dense plasma focus device with input electrical energy lower than 1 kJ [Silva et al. (2001)]. To date two very small plasma focus devices, PF-50J [Silva et al. (2001)] and PF-400J [Silva et al. (2003)] have been developed successfully. The maximum neutron yields obtained from PF-50J and PF-400J discharges were about 10^4 and 10^6 neutrons per pulse, respectively [Soto et al. (2004)]. This confirmed the feasibility of sub kilojoules plasma focus capable of producing pinch plasma and lead to the emission of various radiations.

An ultra-miniature dense pinch plasma focus device operating at only 0.1 Joule was later demonstrated [Soto et al. (2005), Soto et al. (2009)]. Evidence of pinch had been obtained from the electrical signals and optical images. X-ray emission was also reported when hydrogen, argon or neon was used [Pavez et al. (2010)].

The plasma density and electron temperature of the Nanofocus [Milanese et al. (2003)] were reported as 10^{20} cm^{-3} and around 1 keV, respectively. This 125 Joules plasma focus device produced about 10^{6} neutrons per pulse together with intense hard X-ray burst. However, only 10 % of the discharges produced pinched plasma.

Another miniature plasma focus with energy in the range 58 - 160 Joules was operated in repetitive mode [Hassan et al. (2006)]. By employing an optical streak camera, it was found that the typical plasma dynamics at low energy was similar to much larger facilities, thus it was capable of producing in principle all the radiation produced by large facilities. This device was operated with neon and hydrogen. It was found that when hydrogen was used as operating gas, stronger pinching was observed.

A fast miniature plasma focus (FMPF-1) device as a compact and portable nuclear fusion apparatus producing neutrons while operating at 200 Joules was successfully demonstrated by Verma [Verma et al. (2008) 045020]. Average neutron yield of 1×10^{4} neutrons per shot was reported. The author also investigated the effect of krypton seeding in deuterium on neutron emission [Verma et al. (2008) 101501] and

X-ray yield [Verma et al. (2008) 011506] and found that maximum enhancement of around 30-fold and 17-fold were obtained in the neutron emission and X-ray yield, respectively. Recently, FMPF-1 as a compact, portable and cost effective hard X-ray source for good contrast radiography using hydrogen as operating gas was demonstrated [Verma et al. (2010)]. The hard X-ray produced from FMPF-1 was mainly contributed by the electron-beam target mechanism.

From these results stated above, the researchers found that performance of the low energy dense plasma focus devices was similar to the results obtained with devices operating at energies several orders of magnitude higher. However, in terms of the source size and the capability to operate in high repetition mode, the low energy devices had better performance than the large devices in application [Fomenkov et al. (2004), Verma et al (2010)]. Therefore, low energy plasma focus devices broaden the application scope and fulfill the industry’s requirements in terms of performance, size and cost of ownership.

1.3 Plasma Focus Radiation Sources

Plasma focus is capable to produce various radiations from its pinch plasma. Radiation emissions include X-ray to visible light as well as particle beams such as ion beams and electron beams. The characteristics of the radiation source greatly depend on the operating condition. It includes the pressure, operating gas, input energy, geometry of the plasma focus tube and etc. The following sub-sections will mainly focus on the review of X-ray, ion beam and EUV emission from the plasma focus.

1.3.1 X-ray Source

During the plasma pinch phase and the subsequent disruption phase, bursts of ions and electrons, hard X-ray and EUV radiation from the pinched plasma are observed. X-rays are generated in the plasma focus devices, predominantly contributed by bremsstrahlung and recombination of the thermal electrons. Whereas the line emission (non-thermal X-ray) is from the interaction of high energetic electron beam with the anode surface or from the high Z-ions (impurities) present in the system. The energy of the non-thermal X-rays contributed by the electron beam bombardment of the anode can reach up to100 keV [Schneider et al. (1985)].

Bernstein et al. [Bernstein et al. (1971)] studied the time correlation of X-ray spectrum with neutron emission. The X-ray spectrum covers a broad range from 6 keV to 300 keV. He concluded that the neutron emission coincides with the non-thermal X-ray emission above 30 keV, in a manner consistent with the moving boiler model for neutron production.

High energy electrons with energy in the order of few hundred keV [Schneider et al. (1985)] were observed to travel in a beam almost perpendicular to the truncated end of the anode. This electron beam gained energy as they approached the anode [Harries et al. (1978)]. The electric fields required to produce such electron beam was consistent with the anisotropy of ion emission in the plasma focus. Besides, no counter-streaming of high energy electrons from the anode was evident. Anisotropic high energy X-ray (> 50 keV) originated from the bombardment of the high energy electrons (~ 100 keV) at a small region of the anode surface on the axis was observed. Thus the erosion of the anode, which occurred on axis, was due to this phenomenon. However, low energy X-ray of few keV was emanated from the plasma and was approximately isotropic. Therefore the plasma X-ray is observed slightly before the X-ray from the anode. These experimental results were in agreement with the simulation results [Hohl et al. (1977)] and consistent with the beam target model of neutron production [Lee et al. (1971)]. Furthermore, Harries investigated the influence of the evaporated anode material on the bremsstrahlung X-ray emission [Harries et al. (1978)] and found that the intensity of emission was influenced by the density of the anode material, as well as the intensity and energy of the electron beam.

In another simulation work [Wang et al. (1988)], the state of the metallic vapor and the effect of the magnetic field accompanying the beam were considered in the production of X-ray emission from the electron beam bombardment on the solid. Wang claimed that the magnetic field of the beam reduces the number of electrons departing from the target region at the solid anode, especially for the electron beam with high current. The magnetic field above the surface of anode also increases the energy deposition of electron beam to the anode tip by 12 – 33%. Hence the energy distribution of X-ray was altered and the intensity of X-ray with lower energy was increased due to the reentering electrons, while the intensity of higher energy X-ray remains almost unchanged. Thus, the energy of the X-ray becomes lower.

Regarding the X-ray power law, the X-ray intensity was found to be proportional to $E_p^{-\gamma}$ (E_p photon energy, γ = 2 for 7 keV < E_p < 30 keV) [Bernstein et al. (1969), Bernstein et al. (1970)]. While Lee had shown a similar behavior and suggested that the γ in the power law was 4 ± 1 for E_p > 150 keV [Lee et al. (1971)]. These empirical results indicated that the X-ray emission did not agree with plasma bremsstrahlung emission, but originated from anode bombardment of axially accelerated electrons.

Various empirical scaling laws of the soft X-ray production had been investigated and proposed [Serban et al. (1997)]. This new scaling law for the soft X-ray yield expressed in terms of the maximum discharge current I_{max} and the peak axial speed υ_{axial} as $Y_{SX} \sim I^2_{max}\upsilon^4_{axial}$. Another comprehensive X-ray scaling law in a low energy plasma focus with input electrical energy lower than 1.8 kJ was proposed [Sharif et al (2004)] and it was found that the total X-ray emission varies approximately as $Y_T[J] \sim [E\ (kJ)]^{4.5\text{-}5.5}$ or $[I\ (100kA)]^{4.5\text{-}5.5}$, whereas the Cu-$K_\alpha$ line radiation was $Y_K[J] \sim [E\ (kJ)]^{3.5\text{-}4.5}$ or $[I\ (100kA)]^{3.5\text{-}4.5}$. The X-ray emission efficiency of the 1.8 kJ plasma focus was 1.44 ± 0.07% and 32% of the emission was contributed by the Cu- K_α line radiation. Recently, the plasma focus neon soft X-ray scaling laws based on a comprehensive range of numerical experiments with storage energies E_o in the range of 0.2 kJ to 1 MJ had been proposed [Lee et al. (2009)]. Lee proposed that the soft X-ray yield scales as $Y_{sxr}[J] \sim 1.07 \times 10^{-7}\ [I_{pinch}\ (kA)]^{3.63}$ for optimized plasma focus operation. This result indicated that the plasma focus must be designed to optimize I_{pinch} for applications requiring high X-ray yield.

In the work requested by Favre et al. [Favre et al (1992)], X-ray emission from a 3 kJ plasma focus operating with H_2-Ar mixtures was strongly contributed by the electron beam target interaction rather than from the hot high-density plasma. This result was identical with the previous works done by Harries using a high energy plasma focus device as mention earlier. Favre noticed two successive plasma compressions from the evolution of the X-ray emission. Furthermore Ng et al. [Ng et al. (1998)] attempted to eliminate the undesirable X-ray line emission due to electron beam target mechanism on the anode surface by operating the plasma focus device over a wide range of operating pressures. Ng notice that the importance of the operating pressure on the soft X-ray emission and three pressure regimes could be clearly discerned. In the first regime (lower pressure regime) both the plasma X-ray and line emission were weak. In the second regime (intermediate pressure regime), both the emission from the plasma and the contribution from the line emission were strong. In the third pressure regime (higher pressure regime), the plasma X-ray was intense, while the bremsstrahlung X-ray emission was dominant.

Zakaullah et al. [Zakaullah et al. (1996) 360] noticed that optimum X-ray emission occurred within a narrow pressure range of 2.0 - 2.5 mbar for a 2.3 kJ plasma focus. The authors compared the X-ray emission and ion beam qualitatively with three different anode shapes, which were cone-shaped anode, tapered anode and cylindrical flat-end anode in the argon medium [Zakaullah et al. (1996) 544]. In this study, they claimed that the radiation yield and the optimum operating pressure were strongly dependent on the anode shape. In the case of the tapered anode, both X-rays and ion beams emissions were enhanced by threefold. Thus, an appropriate shaping of the anode could toggle the plasma focus discharge to emit high intensity X-ray, to even up to tenfold, as reported in a conventional low energy dense plasma focus device [Bhuyan et al. (2004)].

Zakaullah et al. [Zakaullah et al. (2000)] also investigated the pressure range for the argon K-series line emission from the 2.3 kJ plasma focus and found that the argon line radiation yield was highest at 1.5 mbar with emitted energy of 30 mJ. Whereas the emission at an energy exceeding 3 keV that owing to the interaction of energetic electrons with anode was found to be highest at 0.5 mbar with total yield of 0.7 J. One year later the authors [Zakaullah et al. (2001)] reported the operation of this device in an enhanced Cu-K_α line emission mode. The Cu-K_α line emission of 0.4 J/sr and 0.8 J/sr were recorded in the side-on direction and the end-on direction, respectively. 8 J out of 40 J X-ray emission in 4π geometry were in the form of Cu-K_α line. Subsequently, the authors developed a 1.2 kJ nitrogen plasma focus device as soft X-ray source [Shafiq et al. (2002)] and noticed that this device emits 21.8 joules of soft X-ray emission, which originated from the electron beam bombardment on anode tip.

Based on the interaction of energetic electron beam with anode tip, Zakaullah et al. were able to enhance the X-ray yield by using high-Z metallic disc inserted copper tapered anode tip [Shafiq et al. (2003), Hussain et al. (2003), Hussain et al. (2006)]. Another technique used by the group to enhance the X-ray yield was to pre-ionize the plasma focus [Ahmad et al. (2006) 42, Ahmad et al. (2006) 314, Ahmad et al. (2006) 061503] by a corona discharge at the backwall or alpha particles emitted from depleted uranium. It was found that the pre-ionization enhanced the X-ray emission and reproducibility of the plasma focus operation.

Mohammadi et al. [Mohammadi et al. (2007)] studied the neon soft X-ray emission from the UNU/ICTP PFF operated with longer than optimal anode length. A significant increase in the anode length than the optimal was shown to be still able to produce good neon soft X-ray yield at a new optimum pressure but the plasma focus operation was found to be very sensitive to the operating pressure.

Recently Habibi et al. [Habibi et al. (2010)] reported that the employment of high Z metallic disc inserted anode tip not only increased the hard X-ray intensity but also led to high degree isotropic emission of hard X-ray. Therefore the intensity of hard X-ray and also its isotropy depend on the anode tip materials. However the mechanisms to explain the different behaviors of the hard x-ray from the plasma focus devices were still controversial.

Regarding applications, investigation of UNU/ICTP PFF as a soft X-ray source designed specifically for soft X-ray proximity lithography was reported by Liu et al. [Liu et al. (1998)]. The total energy of soft X-ray yield when operated in pure neon was about 6 joules per shot into 4π steradians. From the spectral data, it was deduced that 64% of the total soft X-ray yield was originated from the line radiation and the rest was mainly contributed by the radioactive recombination. The author proposed that reduction of external inductance might lead to a large increase of the soft X-ray yield.

Furthermore Lee et al. [Lee et al. (1998)] succeeded in developing the 2.2 kJ NX1 [Bogolyubov (1998)] and the 1.9 kJ NX2 with neon as an operating gas for soft X-ray lithography demonstration. The NX1 has high performance and high repetition rate capacity and it is capable of emitting maximum neon plasma soft X-ray yield of over 100 joules compared to 18 joules from NX2 plasma focus. However, the X-ray emission in NX1 plasma focus was found to be due to multiple pinched plasmas. Subsequently investigation of NX2 with argon, krypton or argon admixture filling as a possible radiation source for micromachining had also been done [Gribkov et al. (2002)]. The further enhancement of the soft X-ray yield in NX2 was found to be able to achieve up to 140 J/shot, hence demonstrating the capability of NX2 as a powerful X-ray source for X-ray lithography [Wong et al. (2004)].

Castillo et al. [Castillo et al. (2001)] investigated the hard X-ray produced by non-thermal mechanism by observing its peak duration, source size and radiation intensity. This study was driven by the radiography application of dynamic biological systems. In the demonstration, a 2 kJ plasma focus device with nanosecond emission duration was found to be sufficient to produce ultra-fast radiography of live small biological specimens with a single discharge. Similar result was also reported in another study by using a 3.3 kJ small plasma focus [Hussain et al. (2003)].

1.3.2 Ion Beam Source

The high density high temperature plasma produced by plasma focus is a well known source of pulsed ion beam emission with characteristic energy up to hundreds of keV. In the past, several researchers were involved in the studies on a comprehensive characterization of ion beam emissions, in terms of energy, ion composition, angular distribution and flux in order to understand the ion emission mechanism. By understanding the beam production mechanism, the energetic ion beams can be controlled and used for applications as an intense pulsed ion source for various fields including surface modification, thin film deposition, crystallization and ion implantation.

For ion beam spatial distribution study, Sadowski et al. [Sadowski et al. (1988)] found that the non-symmetrical distribution of ion micro-sources was due to the heterogeneity of local electromagnetic fields which lead the angular distributions of fast ion exhibit a highly anisotropic and the ion emission distributed at θ angles between ± 40º for various dense plasma focus facilities. The first ion pulse was correlated with the first neutron pulse corresponding to the stable phase in the radial compression phase, while the other pulses were generated during the unstable phase. The high energy ions (> 100 keV) were emitted mostly during the unstable phase.

In the year 1993 Bostick et al. [Bostick et al. (1993)] employed a 5.4 kJ plasma focus and observed the ion beams energy in the range of 300 keV to 9.0 MeV in axial direction by using the Time of Flight (TOF) method and confirmed with a differential filter method. They also observed that the ion beam intensity depended significantly on the pressure and was correlated with the neutron yield and the hard X-ray intensity. Specifically the dependence of the ion beam intensity on pressure was similar to the dependence of neutron yield and hard X-ray intensity on pressure. Hence the maximum ion beam intensity and the corresponding neutron yield was found to increase with the hard X-ray intensity.

Heo et al. [Heo et al. (2002)] also measured the argon beam energy by using Faraday cup with TOF method. They found that the maximum energy of the argon ions produced by a 1.9 kJ plasma focus was over 800 keV and majority of the ions had energy at 200 keV. The ion beam emission was observed before the X-ray emission. Ion beam emission was able observed for discharge with no X-ray emission. However stronger ion emission was normally observed when X-ray emission was detected.

Kelly et al. [Kelly et al. (1996) 1931] found that the ion energy spectrum followed a power law with the ion energy of $E^{-\beta}$ ($1.5 < \beta < 2.0$) by employing a Solid State Nuclear Tracks Detector (SSNTD) CR-39. The maximum ion energy was observed to fluctuate between 200 eV to 900 keV. From these results it was concluded that the density of the low energy ion beam is higher and it played an important role in the neutron production in the 5 kJ PF-II.

Yap et al. [Yap et al. (2002)] modified the geometry of the 680 J plasma focus for the investigation of the ion beams at 10^{-3} mbar. They employed two biased ion collectors in the time-of-flight technique to measure the nitrogen ion energy. The ion beam was found to have two components, one with energy of a few hundreds keV and the other low energy component with energy of a few tens of keV. Bhuyan et al. [Bhuyan et al. (2005)] also employed similar technique to measure the ion beam energy from a methane plasma produced by a 1.8 kJ plasma focus. The high energy ions were in the range of 0.9 – 1.1 MeV and dominated by C^{+5}. Besides Bhuyan et al. also studied the ion beam angular distribution and found that the ions exhibited a strong angular anisotropy [Bhuyan et al. (2006)]. Takao et al. [Takao et al. (2003)] measured the nitrogen ion beams and attempted to improve the purity of the beams. They found that the purity of the nitrogen ion beams may be enhanced to reach 91 % by using hollow type anode.

For the applications of the ion beams, Lue et al. [Lue et al. (1983)] was the first group who used the hydrogen ion beams generated by plasma focus as a source for the annealing of ion-implanted semiconductors. The damaged wafers were completely re-grown after it received the plasma annealing process. They also found that the plasma focus annealed wafers depended greatly on the operating pressure and the plasma pinch behaves. Several work on thermal effect of ion implantation and surface treatment with ion beams were also reported [Sánchez et al. (1995), Kelly et al. (1996) 704, Kant et al. (1997)].

1.3.3 EUV Source

Gas Discharge Produced Plasma (GDPP) as EUV source for EUVL is expected to be a low cost of ownership (CoO) and easy to maintain alternative to synchrotron and Laser Produced Plasma. EUV source based on the plasma focus is one of the candidates of GDPP. To achieve strongest EUV emission in the 13.5 nm, a plasma with electron temperature of about 30 eV [Bowering et al. (2004)] and the discharge current of about 20 kV are necessary to generate the plasma [Stamm (2004)].

Partlo et al. [Partlo et al. (1999)] constructed a 200 Hz, 25 joules prototype plasma focus with lithium as working gas. Initial characterization of this prototype showed that it was efficient at converting input energy into in-band EUV emission, which emitted 0.76 joules of the 13.5 nm doubly ionized lithium line giving a conversion efficiency of 3 %. But Fomenkov et al. found that this 25 joules plasma focus was poor in position stability and high input energy leading to large integrated source size and high electrode erosion [Fomenkov et al. (1999)]. Therefore, Fomenkov et al. modified this prototype plasma focus to form small and stable pinch plasma with input energies less than 5 Joules.

Partlo and Femonkov [Partlo et al. (2001), Fomenkov et al. (2002)] also investigated the EUV emission from a 200 Hz repetitive mode 12.4 joules plasma focus by using xenon and helium as working gases. They found that the pressures and flow rates of the gas components had a strong influence on the EUV emission efficiency. The highest conversion efficiency obtained was 0.42 % of input energy. In the year 2002 the conversion efficiency of the total in-band EUV output had been increased to near 0.5 % operated at 4 kHz in burst mode, 1 kHz in continuous mode [Fomenkov et al. (2003)]. Further investigation [Fomenkov et al. (2004) 168, Fomenkov et al. (2004) 3266] for plasma focus operated at 5 kHz in burst mode, 2.3 kHz in continuous mode showed that the conversion efficiency of the plasma focus operated at positive and negative polarity were saturated at 0.5 %. While the conversion efficiency of the total in-band EUV output increased to around 1.7 % or 200 mJ with tin powder as the target element. However the thermal engineering of the central electrode remains a major challenge in the design of plasma focus with repetitive mode.

This was owing to the significant amount of heat deposited on the electrodes. The heat was usually contributed by the energy transferred from the plasma by radiation to the electrodes as well as ohmic heating of the electrodes due to high current flow.

A miniature hybrid plasma focus device, operated with xenon gas and driven by a 10 kA fast current pulse had been used to generate extreme ultraviolet radiation in the range of 6–15 nm [Mohanty et al. (2006)]. The EUV intensity measurement using photodiode showed fairly isotropic radiation at least in a half solid angle.

Recently, Tangjitsomboon [Tangjitsomboon et al. (2009)] used a computation model to determine the suitable parameters for EUV radiation production from UNU/ICTP PFF. In this work, the author simulated the five dynamic phases of the plasma focus, based on Lee model, to calculate the total EUV power from the radiation phase at fixed physical parameters while varying the input energy and operating pressure. The calculated total EUV power consists of bremsstrahlung, recombination and line radiation. From the calculation, xenon discharges with input energy in the range of 184 joules to 454 joules were able to emit 6×10^{10} W to 1.6×10^{11} W of total EUV power at 1 mbar.

Research concerning the EUV source from the compact plasma focus device is being pursued actively and various approaches such as using different working gases and anode materials or modification of the focus tube design are still in progress. Obvious improvements in terms of power of the EUV emission, spatial resolution have been demonstrated in the past few years. The requirement of the EUV power for EUVL is 180 W at the intermediate focus based on a resist sensitivity of 10 mJ/cm^2. To date, the EUV power produced by the plasma focus has not met the basic requirement for EUVL.

From the literature review above, the ion beam emission, X-ray yield and EUV yield in a dense plasma focus depend greatly on the specific design and experimental parameters. These include the electrode configuration, shape and material, circuit inductance and resistance, stored energy that convert to the magnetic field energy driving the plasma, electromagnetic driver parameters, the operating pressure and medium composition. However the operating gas and pressure seem to have the dominant influence on radiation emission.

The purpose of this project is to develop the 600 joules plasma focus as pulsed radiation source and to investigate the optimum operating pressure that is required to set the stage for optimum EUV output. Additionally, the ion beam and ultra-soft radiation in the range of 6Å to 600Å will also be investigated. Therefore, this system can be employed as pulsed radiation source including X-ray, EUV and ion beam emission.

Time resolved measurement of the discharge voltage and current are made by using the resistive voltage divider and Rogowski coil, respectively. Several radiation measurement tools such as biased ion collector, X-Ray Diode (XRD) and IRD-SXUV5A EUV detector are used in order to investigate the radiation production from the dense plasma focus device.

1.4 Layout of this Dissertation

The dissertation is organized in the following manner:

Chapter 1 (Introduction) presents the motivation of this project and reviews the literature of the plasma focus works.

The principle of operation and design concept of a 600 joules small plasma focus are presented in Chapter 2 (Plasma Focus Discharge Characteristics). The overview of the plasma focus dynamic model is also explained.

Chapter 3 (Experiment Setup) presents the arrangement of the 600 joules small plasma focus device and experimental setup used in this project. The diagnostic tools and their calibration will be described.

In chapter 4 (Results and Discussion), the experimental results and discussion are presented. These include the EUV and ion beam results and analysis. Discussion on voltage spike, XRD emission and EUV emission correlation are presented.

Chapter 5 (Conclusion) contains the summary of the results, the conclusions and some suggestion for future work.