Chapter 1

Introduction

This chapter reviews research on helicon waves starting with their initial identification as whistler waves in the ionosphere. Then it looks at the extensive studies in solid state plasmas, and finishes with current work on industrial applications of gaseous plasmas produced by helicon waves. Chapter 2 details the experimental apparatus called Basil with which the results presented in this thesis were obtained, together with the diagnostics used to obtain these results. Chapter 3 presents theory used to understand helicon wave propagation in uniform plasmas. Detailed wave and plasma measurements are presented in chapter 4, for a plasma produced using a double saddle coil antenna. Chapter 5 presents measurements of the asymmetric plasma produced using a helical antenna and also details attempts to control the azimuthal mode make-up of the launched helicon wave by using a phased antenna. Finally, chapter 6 examines the evolution of the plasma discharge and describes a simple 1-D model used to understand the diffusion processes which are important during the initial stages of the discharge.

1.1 Review of Helicon Wave Studies

Accidental observations of the ionospheric equivalent of the helicon plasma wave, called the whistler wave, date back to 1886 when whistlers were observed on a telephone line at the Sonnblick High Altitude Observatory in Austria [51]. Reliable observation of whistler became possible when high gain valve amplifiers became available. It was reported by Barkhausen [6] that during World War One that (when high gain amplifiers were used by both sides to spy on enemy communications) “At certain times a very remarkable whistling note is heard in the telephone. At the front it was said that one hears “the grenades fly” ”.

Interest in whistler waves was rekindled by advances in communication technology, when interference to long distance communications became important. An example of this was the measurement of interference on a submarine cable in Trinity Bay, Newfoundland, in 1930 [26, 27].

In 1953 Storey [107] gave a detailed explanation of the phenomenon of whistler waves, describing their origins, experimental techniques, and analysing recorded data. Also presented was a detailed theory of the origins of whistler waves in the atmosphere, which was based on the work of Barkhausen [5], Darwin [40], and Eckersley [47]. Storey explained how whistlers are waves propagating through the upper ionosphere guided along the earth’s magnetic field lines. The whistling tone is produced by dispersion of the wave as it propagates through the ionosphere. The origins of the wave were concluded to be lightning flashes, which explained the two types of whistlers observed: short and long whistlers. Short whistlers being waves detected in the opposite hemisphere to their origin, and thus only having travelled one transit of the ionosphere. While long whistlers are those waves detected in the hemisphere of origin, having thus made two transits of the ionosphere, and are therefore more dispersed. Long whistlers are also often proceeded by a click corresponding to direct radiation from the lightning strike. A very detailed study of the observation of whistlers was made by Helliwell and Morgan [59] in 1959.

In 1960 Aigrain [1] suggested the possibility of observing whistler waves in a solid state laboratory plasma. Aigrain called the wave a helicon wave because of the rotation of the electric field as the wave propagates along the magnetic field lines, tracing out a helix. Much of the early work on helicon waves was in solid state plasmas because of an immediate use as a diagnostic for measuring Hall coefficients in pure metals. The early experiments in gaseous plasmas were also motivated by the possibilty of a diagnostic, for measuring plasma density and static magnetic field strengths.

The recent resurgence in helicon wave studies was triggered by Boswell and Henry [18] who reported the use of a helicon wave produced plasma for etching materials used in the micro-electronics industry. Plasma sources using helicon waves are now commercially available for both etching and deposition processes utilising a range of materials. Much of the present work in this field is aimed at understanding the properties of these plasma sources so that devices with industrial applications can be designed with less guess work and a greater control over the plasma characteristics.

Another application of helicon wave produced plasmas was an argon ion laser by Zhu [112, 114, 113]. The use of helicon waves to produce plasma in fusion machines has been studied by Loewenhardt et al [81] and Borg et al [12], Chen [33] suggests using helicon wave produced high density plasmas in high energy particle accelerators.

1.1.1 Theoretical Treatment of Helicon Waves

General hydromagnetic waves were investigated by numerous authors [111] in the late 50's. Detailed theoretical treatment of helicon waves was first carried out by Klozenberg, McNamara and Thonemann [70]. Their work, which has become known as the KMT theory, derives the dispersion relation of helicon waves in a uniform plasma with a vacuum boundary. Using numerical methods they obtained dispersion relations and radial wavefields for $m = 0$, $m = +1$ and $m = -1$ mode helicon waves.

The first attempt at theoretically treating helicon waves in a non-uniform plasma was by Blevin and Christiansen [9]. Because of the number of simplifying assumptions that were needed to make the problem solvable, their theory did not compare well to experimental data. However, their results showed trends that would help the KMT theory agree better with experimental results.

A theory for helicon waves in non-resistive cylindrical and spherical plasmas was developed by Francey and Gates [50]. The motivation for studying a spherical plasma was the possibility of observing the interaction of helicon waves with other waves, such as acoustic waves, in a solid state plasma.

Perfectly conducting boundary conditions were treated by Ferrari and Klozenberg [49] who calculated the dispersion relation and attenuation for a uniform plasma. Treatment of the effects on radial mode structure for different boundary conditions was treated by Boswell [16].

1.1.2 Helicon Waves in Gaseous Plasmas

The first laboratory experiment with helicon waves involved the observation of the transmission of microwave frequency whistler mode waves by Gallet et al [53] in a dense plasma produced in the ZETA torus fusion machine at Harwell, England. It was hoped that by measuring the propagation of this wave that this would be useful as a diagnostic for measuring electron density and static magnetic fields. Other early experiments involving whistler waves at microwave frequencies included the measurement of the refractive index for the transmission of 3cm microwaves in the afterglow of a linear argon plasma by Dellis and Weaver [44], who then went on to measure the dispersion relation [45]. Mahaffey [83] investigated the prospect of using the transmission of whistler waves as a diagnostic by taking measurements over a wide range of conditions in an argon discharge.

The first reported experiment of whistler waves at rf frequencies was by Hooke et al [62]. They produced a plasma with an induction coil oscillating at 16MHz, then reduced the rf power and measured the transmission of waves from the induction coil to a pickup coil in the afterglow. By moving the position of the pickup coil they measured the phase of the wave versus position, demonstrating the propagation of the wave.

Jephcott and Malein [67], also working at rf frequencies, were able to make detailed measurements of dispersion curves and radial magnetic wavefields by exciting an m=0 mode wave with a single loop antenna. The wave was launched in an argon plasma preformed by a DC discharge at 50mTorr and having an applied static field up to 6kGauss.

Anomalously high damping was first observed by Kovan et al [73] and the explanation of Cerenkov damping (later referred to as Landau damping) was put forward by Dolgopolov et al [46] and Nazarov et al [92], who also compared their theory to experimental results. The experimental work of Kovan et al was also one of the earliest experiments of launching rf frequency helicon waves in a preformed plasma. They launched waves in the frequency range of 2 to 25MHz into a preformed plasma with a density in the 10^{19}m^{-3} range, with an applied magnetic field of between 0.1 Tesla and 0.3 Tesla. They made detailed measurements of the radial wavefield structure and the damping of the wave.

Experiments aimed at obtaining results that could be compared to the KMT theory were carried out by Lehane and Thonemann [78]. They produced a plasma with an array of nine two turn coils in parallel, spaced along a 10cm diameter pyrex glass vacuum vessel, which was excited by 3kW of rf power in the frequency range of 15MHz to 17MHz. They excited an $m = 0$ mode wave with a two-turn loop around the vacuum vessel, and the $m = +1$ mode with a single loop inside the plasma with its axis normal to the plasma axis. They also attempted to excite $m = -1$ mode waves with two loops at right angles and phasing the currents by 90^0 or 270^0. They used centre tapped magnetic probes to measure the radial and longitudinal variation of the wavefields. Radial plasma densities were measured with a Langmuir probe. They compared their measured dispersion curves and radial wavefield measurements with the KMT theory and found reasonable agreement. Dispersion curves were also measured by Davies and Christiansen [41] for helicon waves, but for a frequency range just under the electron cyclotron frequency $(0.1\omega_{ce} \leq \omega \leq 0.5\omega_{ce})$.

Experiments concentrating on the production of plasma by helicon waves and the mechanisms involved, as well as the properties of the wave propagating in the plasma, started with Boswell [14, 13]. In these experiments a plasma was produced by a helicon wave launched by a double loop antenna and the characteristics of the plasma and the wave were studied. With an applied field of up to 1500 gauss and rf power of 600 watts at 8MHz he produced plasmas in a 10cm radius Pyrex tube with a peak density of around $4 \times 10^{12}\text{cm}^{-3}$. The study of helicon wave production of plasmas, in particular examining the mechanism for high density production is currently a popular field of study, with recent work carried out by Boswell [17], Komori et al [72], and Shoji et al [102].

The importance of including the electron cyclotron resonance in calculating the dispersion relation for helicon waves was first noted by Blevin et al [10] in comparing their experimental results with theories, with and without electron inertia. Electron cyclotron damping of helicon waves near the electron cyclotron frequency was verified by Minami and Takeda [91], McVey and Scharer [87], and Christopoulos et al [36]. While the results of Minami and Takeda were not conclusive and McVey and Scharer measured damping along a weak magnetic beach, Christopoulos et al found good agreement with a more complete theory by Olson [93] in a uniform magnetic field.

When the excitation frequency of a wave is less than the electron cyclotron frequency, then a resonance cone of the wavefield is produced with an angle of $\theta = \sin^{-1}(\omega/\omega_{ce})$. Using an excitation frequency of half the electron cyclotron frequency Boswell [15] measured the resonance cone for whistler waves.

1.1.3 Helicon Waves in Solid State Plasmas

The propagation of helicon waves in a semiconductor in a magnetic field was first proposed by Aigrain [1]. In his paper Aigrain described the main characteristics of helicon waves and proposed experiments for their detection in a semiconductor, he also calculated the frequency for a known carrier density and applied magnetic field.

Bean et al [7] described an experiment to measure the resistivity of a very pure metal by measuring the decay time of eddy-currents (detected by the induced voltage in a pickup coil) when an external magnetic field was suddenly removed. By measuring the exponential decay of the eddy-currents they calculated the resistivity of a number of metals. In a very similar experimental setup Bowers et al [21] applied a static magnetic field perpendicular to the field that is removed, and the detection coil. After removal of the field, instead of a simple exponential decay they observed a damped oscillation. The frequency of this oscillation was found to be proportional to the transverse magnetic field (35Hz at 10000 Gauss) and Bowers et al realized there was a connection with the waves proposed by Aigrain, but at a much higher carrier density and thus lower frequency. Soon after being observed in metals helicon wave propagation was demonstrated in a semiconductor by Libchaber and Veilex [79] who observed the transmission of microwaves through a thin slab of InSb at 10GHz, the frequency calculated by Aigrain.

Chambers and Jones [28] used the experiment of Bowers et al [21] to measure the high field Hall effect. They developed a theory that related the Hall coefficient, the resistivity and the sample shape to the resonant helicon frequency. They went on to measure the Hall coefficient of Li, Na, K, Al and In at 4.2K. Similar experiments that measured Hall coefficients and detected higher order helicon modes with higher accuracy were performed by Rose et al [99], Cotti et al [37], Taylor et al [110] and Merrill et al [89]. The higher order modes were found by observing standing wave resonances in a sample when the wave was driven by an external oscillating field. Stern [105] hypothesised that these helicon waves in metals would be damped by Doppler shifted cyclotron absorption and this was observed experimentally by Taylor et al [110] in thin plates of sodium. Stern [105] proposed using the frequency at which the absorption occurred to determine the shape of the Fermi surface.

The properties of helicon waves effected by Doppler shifted cyclotron resonance, the effect on the surface impedance of metals, skin effect conditions and effects of open orbits have been considered by McGroody et al [86], Sheard [101], Baraff and Buchsbaum [4], Overhauser and Rodriguez [94], and Buchsbaum and Wolff [25]. A theory for non-local damping of helicon waves was developed by Kaner and Skobov [69], Buchsbaum and Platzmann [24] and extended by Houck and Bowers [63], who also made comparisons to experimental results along with Hui [65]. Miller [90] and Quinn [98] calculated the absorption of propagating helicon waves with a quantum model and found large oscillations occurred in certain regimes.

Legendy [77] developed a macroscopic theory of helicon waves treating the boundary-value problems for the sample geometries used in solid state experiments and found that under certain conditions an unusual surface mode appeared. Experimental work by Goodman [54] and Amundsen [3] demonstrated the boundary conditions of Legendy to be correct. Goodman detected the power dissipative surface mode and both made very accurate measurements of Hall coefficients. Alais [2] developed a theory for propagation of helicon waves in simple geometries with translational or circular symmetry and calculated the first two resonances in a sectional barrel.

Harding and Thonemann [58] used a 9.4cm long, 0.8cm diameter sample of indium at 4.2^{0}K to study the phase velocity and attenuation of helicon waves. They used a single coil to launch $m = 0$ waves and two coils phased 90^0 to each other in order to launch

$m = +1$ and $m = -1$ waves. By moving the detection coil along the length of the sample the phase velocity and damping was measured. These results were compared to the theory of Klozenberg et al [70] (the KMT theory). The KMT theory was also compared to measured dispersion relations of higher order harmonics in cylinders of Na and In by Hui [64].

The interaction of helicon waves and phonons (acoustic waves) in a solid was proposed by Langenberg and Bok [75], Quinn and Rodriguez [98] and Skobov and Kaner [103]. Coupling between the two waves was observed by Grimes and Buchsbaum [56] in potassium and was found to be a maximum when the phase velocity of the two waves were equal (as expected). Another form of interaction considered by Stern and Cullen [105] was between helicon waves and magnons (a spin-wave in a magnetically ordered conductor) and this was observed in nickel by Grimes [55].

An undergraduate experiment was proposed by Merrill et al [88] using helicon waves to measure Hall coefficients. It proposed using two methods, a swept frequency method to find standing wave resonances in a sample and a measurement of the decaying oscillation when an external field is removed to determine the helicon wave frequency. An early review of the use of solid state plasma to study helicon waves was done by Bowers [22] and a thorough review of experiment and theory of helicon waves in solids was done by Maxfield [84].

1.1.4 Helicon Waves in Plasma Production for Surface Modification of Materials

The micro-electronics industry requires fabrication of structures with dimensions of the order of microns. Micro-electronic circuit production is generally a complicated multi-step process in which layers of different materials are built up on a substrate base in the appropriate patterns. Considering a simple one-layer device a layer of material such as $Si0_2$ is deposited on the substrate and then a mask with the pattern of the circuit is applied to the surface by a technique known as photolithography. The material not covered by the mask can then be removed using some type of etching process.

Prior to the early '70's etching was predominately carried out by chemical or wet etching, in which the device is immersed in a chemical etchant such as hydrofluric acid. Wet etching is an isotropic processing since etching occurs laterally as well as perpendicularly to the surface. This causes undercutting of the edge of the mask, and when the mask is not well adhered to the substrate, surface lifting can occur resulting in poor dimensional control. Typically wet etching is only viable for structures with 5 nm linewidths.

As devices have become smaller and more closely spaced it is critical that etching take place preferentially in the vertical direction in order to maintain straight side-walls and good device separation. This is especially true for high aspect ratio devices, such as deep trench capacitors, which have small widths relative to their depth. Plasma or dry etching is a process in which the substrate is placed in a plasma and the surface is bombarded with ions accelerated out of the plasma. Ions are accelerated by the high electric fields present in the region where the plasma makes contact with the substrate (the sheath). These fields are directed perpendicular to the substrate surface. So in theory the ion trajectories are also, resulting in anisotropic perpendicular etching of the substrate with little undercutting of the mask. The etch rate in this process is related to both the flux of ions and the energy with which they arrive at the surface and so the etch rate can be manipulated by changing the plasma density and controlling the substrate potential relative to the plasma potential.

Etching is currently understood to occur through two means - mechanically through sputtering, in which ions physically knock out the surface material, and chemically through reactions of neutral radicals produced in the plasma with surface atoms of the substrate, resulting in the formation of volatile products which can then diffuse from the surface. In the second method, known as reactive ion etching (RIE), the plasma chemistry must be chosen correctly so as to produce neutrals which will react with the substrate material. In 1985 Boswell and Henry [18] first used RIE in a helicon source reactor to produce high etching rates of Si/SiO_2 with good selectivity.

As previously mentioned, micro-circuit manufacturing also involves growing layers of material. For many applications, in particular for optoelectronic devices such as buried waveguides, it is important to precisely control the chemical composition of the layers and to avoid introduction of impurities which can result in site defects. Plasmas are also used in growing these layers in a process known as deposition. The plasma consists of a mixtures of gases which can chemically combine on the substrate surface, for example SiH_4 and O_2 are used to produce layers of SiO_2 used in wave-guides. Controlling the ratios of the gases determines the chemical composition of the deposited layer.

Helicon wave produced plasmas have been used for both etching and deposition. For both applications the helicon plasma source is used to provide a dense plasma which then diffuses into a processing chamber in which the substrate is placed. This allows separation of the source of the plasma and the processing region. Helicon sources produce high density plasmas at low gas pressures. The result is a plasma processing system with many advantages.

The separation of the plasma source from the diffusion region in which the processing takes place results in high uniformity over ever increasing areas. The low pressure, reduces ion collisions in the sheath and along with the ability to apply r.f. bias voltages to substrates, results in ion energy distributions with large perpendicular components, and thus highly selective etching. The high densities obtained results in high deposition and etch rates while the diffusion results in good uniformity, and the ability to control the gas chemistry gives a precise control over the refractive index of material being deposited.

Because of the scope of this field it is impossible to list even a fraction of the published work related to surface modification where the plasma was produced using helicon waves. However, a sample of the work by the group headed by Boswell that shows the range of the field includes papers on etching in pulsed plasmas [18, 20], fast anisotropic etching of silicon [96], multipole confined diffusion plasma [19], plasma characteristics of a helicon source for plasma processing [97], and silicon dioxide films deposited in a helicon diffusion reactor [29].