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Low Energy Ion Etching of GaAs and Si Using a New Type of Ion Source Excited by an Electron Beam

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A new type of electron beam excited plasma (EBEP) system which can supply high ion current at low ion energy was developed. Anisotropic ion etching with high etching rate were obtained by Cl_2 reactive ion beam etching (RIBE) and Ar ion beam etching (IBE) in the energy range of 5 -100 eV. At ultra low ion energy of 5 eV, anisotropic etching of GaAs and Si were successfully realized by Cl_2 RIBE for the first time. The etching rate for GaAs and Si are 1.2 and 0.52 µm/min., respectively. High selective ratios of the etching rates for GaAs/SiO_2 and Si/SiO_2 were also achieved.

1. Introduction

In the recent years, dry etching techniques have become more and more attractive since they exhibit unique ability to produce anisotropic etching profile and to be applied into optoelectronic integrated circuit (OEIC) as well as VLSI. A number of dry etching techniques were studied and some excellent results have been achieved[1,2,3]. In the studies, however, high ion energy was generally used for getting available etching rate. For example, RIBE was generally carried out under an extraction voltage of 400 V or more by using an electron cyclotron resonance (ECR) plasma system. The etching rate is an order of 0.1 um/min.

In fact, high energy ions always introduce some radiation damage to the etched samples. Ideality factors (n-values) measured from the forward I - V characteristics indicated that the ion acceleration voltage should be less than 100V for RIBE induced damage to be considerably small and to be similar to that induced by etching with chemical solution[4]. In a conventional ion etching system such as ECR system, unfortunately, the ion current at low ion energy range is too low to obtain appropriate etching rate. Some researchers adapted two-step etching with the first high-energy, and so, high-rate RIBE and the second low-energy slight RIBE for the damage removal[5].

If damageless ion beam etching is carried out in one process, it is necessary to increase ion current at low acceleration voltage. To meet this requirement, we have specially developed a new type of electron beam excited plasma (EBEP) system[6] which can supply very high ion current at ion energy range of 5 - 130 eV. In the study, anisotropic Ar IBE and Cl_2 RIBE were investigated in the ion energy of 5 to 100 eV. The experimental results, including anisotropic etching profile, high etching rate, high selectivity and others, were presented. The degree of damage for the samples etched by the low energy ions was also examined by some measurements.

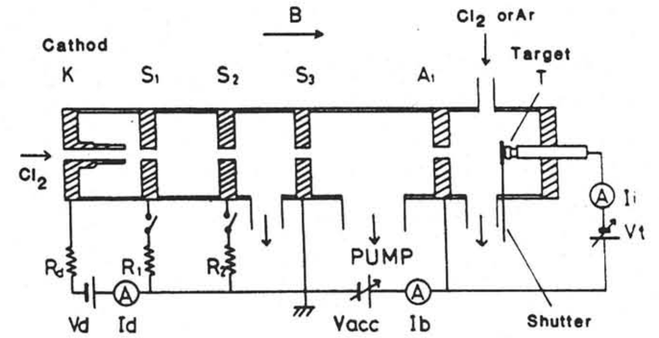

Fig. 1 Schematic diagram of the electron beam excitedplasma (EBEP) system.

2. Experiment

A) Apparatus

The present electron beam excited plasma (EBEP) system is schematically shown in Fig. 1. The EBEP system consists of three sections: a glow discharge plasma region, an electron accelerating region and an ion source region. A uniform axial magnetic field of 600 G is applied to the ion source to prevent the electron beam and the plasma from diffusing to the wall. Cl_2 or Ar gas is fed into the ion source region and its flux is controlled by a mass flow meter. The gas pressure can be changed from 10^{-5} to 10^{-3} Torr. In front of the target, there is a shutter which can be used to measure the ion current accurately and control the etching time.

B) Ar IBE and Cl_2 RIBE

SiO_2 films on the surfaces of GaAs and Si grown by CVD process were used as a mask material. Ar IBE and Cl_2 RIBE of GaAs and Si were carried out at various operation conditions. The etching depth, profiles and morphology were observed by a scanning electron microscopy (SEM). The etching rate as a function of the ion energy was studied intensively.The gas pressure dependence of the etching rates and the selective etching ratio between the semiconductors and the mask material were also investigated. The radiation damage induced by the dry etching at low ion energy was examined by photoluminescence (PL) and deep level transient spectroscopy (DLTS) measurements of the etched samples.

3. Result and discussion

A) Ion source excited by electron beam

The electron beam injected into the ion source region produces a high density plasma. When the potential of the target is lower than the plasma potential, plasma ions are accelerated in an ion sheath in front of target T and strike the target surface as an ion beam. The ion current is proportional to the glow discharge current. When the discharge current is 3 A, the ion current at the extraction voltage of 130 V and Ar gas pressure of 2.2×10^{-3} Torr exceeds 1.1 A, which corresponds to an ion current density 620 mA/cm^2 for the diameter of the target of 1.5 cm. The diameter of the ion beam can be enlarged by reducing the axial magnetic field in the ion source region. So the system is available for samples with large areas. At low ion energy range, the ion density of several hundreds mA/cm^2 can be easily obtained, which is high enough for many practical applications.

There are two reasons why we can obtain high ion current by means of the EBEP system. First, the facility is a kind of the beam-plasma ion source which is based on collective effects of the beam-plasma interaction. The high density plasma is produced effectively by electron beam which has a large atomic ionization cross section. Second, there is a strong electric field in the plasma region along the magnetic field. It means that the ion flow towards the target in the ion source region is induced by the electric field.

B) Etching rate of GaAs and Si

The etching rate in the study is sufficiently reproducible and high enough to assure its utility for devices manufacturing practice. Fig. 2 shows the etching rates R of GaAs and Si as a function of ion

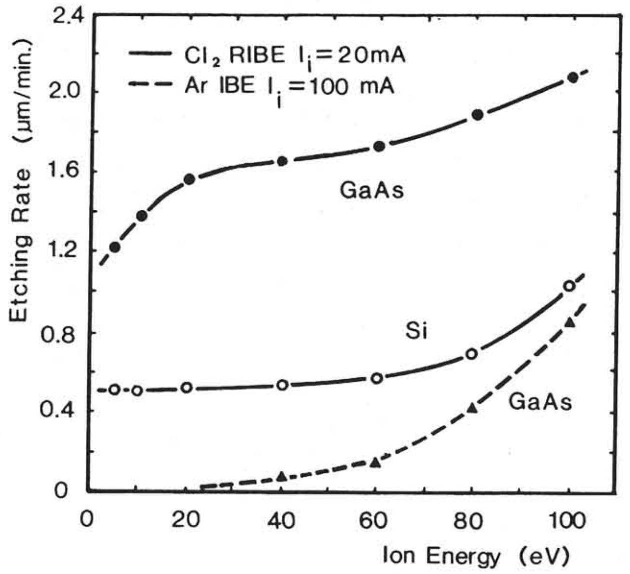

Fig. 2 Etching rate as a function of the ion energy. Cl_2 RIBE (solid lines) and Ar IBE (broken line) were carried out at I_i of 20 and 100 mA, respectively.

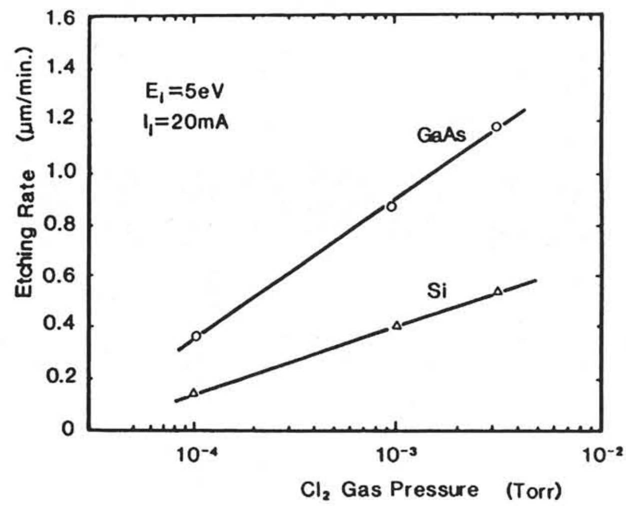

Fig. 3 Cl_2 gas pressure dependence of etching rates for GaAs and Si at E_i of 5 eV and I_i of 20 mA.

acceleration energy. In Cl_2 RIBE process, the ion beam current I_i and Cl_2 gas pressure P_{Cl} were kept constant. They were I_i of 20 mA and P_{Cl} of 3.3 10^{-3} Torr, respectively. Since the diameter of the ion beam is 2 cm, I_i of 20 mA corresponds to ion beam density J_i of 6.37 mA/cm^2. It is clear from Fig.2 that high etching rates for GaAs and Si, R_{GaAs} of 1.73 um/min. and R_{Si} of 0.55 um/min., have been achieved at E_i of 60 eV. Even at the ultra low ion energy of 5 eV, R_{GaAs} and R_{Si} are still as high as 1.2 and 0.52 um/min., respectively. To our knowledge, this is the lowest ion energy for dry etching reported so far. The Ar IBE rate of GaAs is also showed in the same figure. However, the etching process was carried out at ion beam current I_i of 100 mA, which is 5 times that used in Cl_2 RIBE process. We have also found that the etching rates in both cases of Cl_2 RIBE and Ar IBE are proportional to the ion beam current density. Since the EBEP system can supply higher ion beam current density, the etching rate can be increased to higher values.

Cl_2 gas pressure dependence of etching rates for GaAs and Si shown in Fig. 3 indicated that both of R_{GaAs} and R_{Si} increase with Cl_2 gas pressure dramatically. The results also demonstrated that the EBEP system can be operated at a very wide gas pressure range.

In the ion energy range used in the study, etching rate in Ar IBE process increases with ion acceleration voltage exponentially. But for Cl_2 RIBE process it does not depends on ion beam energy so strongly. At E_i of 20 eV, R_{GaAs} in Ar IBE process is so small that we could not detect it. We consider that physical sputtering is the dominate process in Ar IBE. The ion energy must exceed a threshold value of about 20 eV for sputtering to occur at all. Under Cl_2 RIBE process, sputtering can produces only a small contribution to the etching rate. Of much great importance is the effect that impacting ion can have on chemical reactions occurring at the surface. The ion-assisted reactions between neutral etchant species derived from the plasma and solid surfaces play a dominant role in Cl_2 RIBE process.

C) Anisotropic etching and selectivity

Fig.4 shows a typical scanning electron

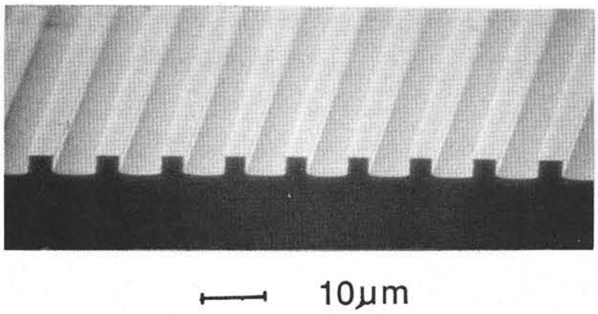

Fig.4 A typical SEM photograph of GaAs anisotropic etching profile. The etching conditions were E_i of 60 eV, I_i of 12 mA and P_{Cl} of 1.9×10^{-3} Torr, respectively.

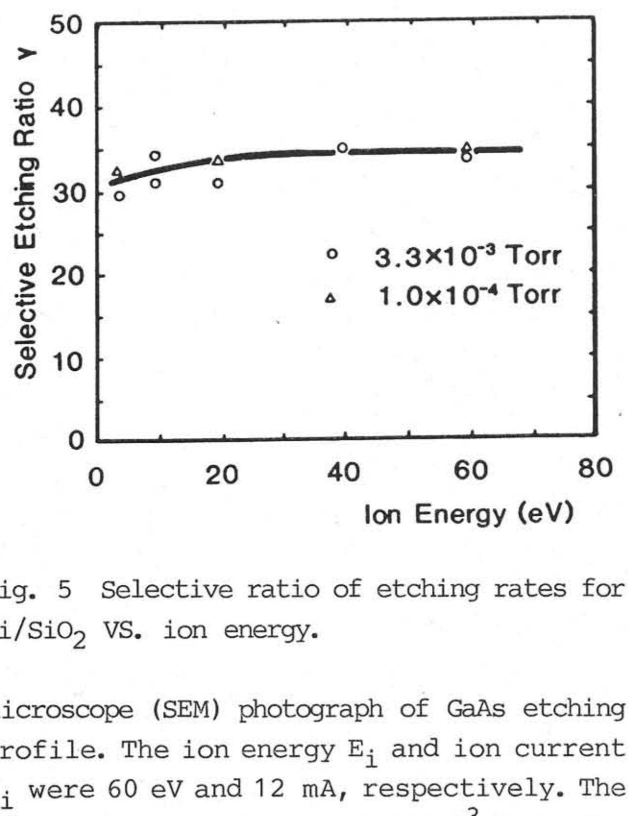

Fig. 5 Selective ratio of etching rates for Si/SiO_2 VS. ion energy.

microscope (SEM) photograph of GaAs etching profile. The ion energy E_i and ion current I_i were 60 eV and 12 mA, respectively. The Cl_2 gas pressure P_{Cl} was 1.9×10^{-3} Torr. The etching depth for etching time of 5 min. was 4.8 μm, which is a value available for devices fabrication practice.

In order to realize the micro-fabrication of GaAs and Si, it is necessary to obtain a high ratio between the etching rates of semiconductors and mask materials. High selectivity in the low ion energy was also demonstrated (Fig. 5). In Cl_2 RIBE process, the selective ratio of etching rates between Si/SiO_2 is about 33 and the ratio for $GaAs/SiO_2$ is 2-3 times the value.

4. Summary

A new type of electron beam excited plasma named EBEP system was specially developed for low energy etching. Compare with a conventional ECR system, the EBEP system exhibits the features: high ion beam current density (several hundreds mA/cm^2) at low ion energy of 5 - 130 eV, independent control of its parameters and operation at low gas pressure.

By using chlorine or argon ion beam with high ion current at the energy range of 5 - 100 eV, anisotropic etching profile, highetching rates and high selective ratio of etching rate were demonstrated for the first time. The results indicated that the low ion energy etching technique can be used for manufacture of microelectronic and optoelectronic devices.

The photo luminescence (PL) and deep level transient spectroscopy (DLTS) measurements of the samples etched at the ion energy of 5 - 100 eV are under studying. The preliminary results indicated that the radiation damage induced by the low energy ion beam is negligible.

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