Effect of quantization noise on the accuracy of Langmuir probe Measurements using DSO

Chirag Senjaliya[A], Pawandeep Singh[B], Shantanu Kumar Karkari[C]

***Abstract*— With the recent advancement in digital electronics, a wide range of Digital Storage Oscilloscopes (DSO) are widely used instead of conventional analog oscilloscope. In-spite of having numerous advantages, the DSO's has also some disadvantages. DSO converts the incoming analog signal into digital form by sampling and quantization. This phenomena leads to data inaccuracy due to amplitude quantization in DSO; which can be viewed as a form of random noise. The effect of this noise reduces the accuracy of measurements performed in plasma systems, particularly during low values of SNR. To highlight the quantization effect of data in a noisy plasma environment; in this paper, experimental results are presented to demonstrate the reduction in the accuracy of Langmuir probe measurements carried in a capacitively driven RF plasma. The dependency of SNR with various parameters namely the number of quantization bits, dynamic voltage range and background noise level have been simulated using MATLAB under experimental conditions. A qualitative discussion has been presented to account the uncertainty in the values of positive ion saturation current measurements using Langmuir probes.**

Keywords—Digital Storage Oscilloscope (DSO), Signal to Noise Ratio (SNR), Quantization Noise, Signal to Quantization Noise Ratio (SQNR)

I. INTRODUCTION

Plasma science and technology is a widely popular subject that applies to space, fusion, and in varieties of industrial plasma applications. In semiconductor industries, capacitively coupled plasmas (CCP) are widely employed for material surface processing [2], [3]. The (CCP) discharges functioned by radio frequency (RF) power supplies are used in technological applications ranging from plasma dry etching [5] to medical applications such as sterilization or wound healing [6], [7], surface treatment, and cleaning [8], microelectronics [9]–[11] such as magnetic [12], diamond-like carbon [13], biomaterial thin films and flat panel display fabrication; transparent conductive oxides film preparation for solar cells [9], [11], [14], mobile phones, and many other rapidly growing areas in material processing [3]–[4], [7]. Plasma measurements are quite essential in order to optimize these systems.

In CCP discharges, typically operated in the MHz range, high amplitude oscillations in plasma potential are generally observed. This makes the measurement of plasma parameters extremely difficult in RF environment. In addition, some random noise is always present in the environment due to radiation from un-shielded vacuum electrical feed-thru or due to improper grounding, which can interfere with the measurements. To overcome the first challenge, compensated Langmuir probe is generally used to measure the plasma parameters. However absolute compensation of RF and its harmonics are quite difficult to remove. The current drawn by the Langmuir probe is measured with help of a current measuring resistance, which is kept at a minimal value as compared to the plasma sheath resistance. Due to this, the voltage drops across the resistor corresponding to ion saturation current tends to be quite small. Sometimes this voltage drop can become comparable to the random noise, in that case it is very difficult to extract useful information from the measured probe signal.

The digital oscilloscope is an inherent choice in plasma measurement because it provides the data storing facility; which is required for post-processing of measured data for plasma parameter extraction. Typically, the experimental probe current signal (differential voltage across the measurement resistor) in low-pressure capacitive RF discharge varies from an mV to a few 10's of Volts as the probe bias is swept relative to the plasma potential. Due to this large dynamic voltage range, the effect occurring due to quantization noise is significantly enhanced during acquisition of lower probe current signal. It is experimentally observed that even if the SNR values are > 1, by changing the voltage dynamic range contributes to a significant variation in the measured DC signal in the DSO. The quantization inaccuracy can be viewed as a form of random noise with a rectangular probability density function of width Δ and variance delta Δ2/12 [15]. In higher bit DSO, this quantization noise is very small and its effect on measurement is not significant; provided that SNR is high. But it can alter the data, if the signal is too small and random noise is in the measurement environment is high. So, in a noisy environment, contribution from quantization noise in measurement must be taken care of.

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In the present paper, experimental results are presented to demonstrate the effect of quantization noise on small signal measurement in a noisy environment. It is observed that the mean value of the probe signal for a given bias voltage to the probe is affected by simply changing the dynamic range (Amplitude Scale) of DSO [Tektronix TDS 3034C]; specifically, when a small signal is measured with a large dynamic range of oscilloscope, provided that the mean value of information signal is slightly greater than the peak-to-peak random variations. This is a specific condition where the SNR value of the signal is slightly greater than the unity. This is even observed when the SNR value is few times greater unity. This inaccuracy in the plasma parameters could significantly mislead while optimizing the plasma system.

II. Quantization Effects

The SNR (signal-to-noise ratio) is defined as the ratio of the signal power ($Psignal$) to the power of background noise ($Pnoise$):

$$SNR = \frac{Psignal}{Pnoise} \tag{2.1}$$

An alternative definition of SNR is as the reciprocal of the coefficient of variation, i.e., the ratio of the mean (μ) to standard deviation (σ) of a signal or measurement:[1][4]

$$SNR = \frac{\mu}{\sigma} \tag{2.2}$$

Equation (2.1) and (2.2) does not take into account for the quantization noise when the signal is acquired in DSO. During the digitization of the signal, the input signal is sampled, quantized and encoded into finite number of levels by a DSO. In the above process, quantization noise is added to the information. This is usually can be ignored if the SNR is sufficiently large. However, for a small amplitude signal, a small contribution of quantization noise could dramatically alter the information. Thus, the contribution of quantization noise can be added by modifying the definition of SNR stated in eq. (2.1) and (2.2) with an effective SNR as follows:

$$Effective\ SNR = \frac{Psignal}{Pnoise + Pqn} \tag{2.3}$$

$$Effective\ SNR = \frac{\mu}{\sigma'} \tag{2.4}$$

Where, Pqn is the power of quantization noise and σ' is standard deviation of the signal after taking the account of quantization noise (variance of a signal after digitization).

The quantization noise is basically an amplitude error, it depends on the number of quantization levels; alternatively on the number of bits are used during the digitization. For a particular DSO, the number of bits are fixed; hence the number of the levels are also fixed.

To minimize the effect of quantization error, the number of levels used for digitization must be high; hence smaller step size eventually results in low amplitude errors. In the case of DSO, the number of levels are fixed; so, the step size is decided by the dynamic range (amplitude scale) of DSO. The total number of levels are distributed in the entire amplitude scale of DSO, hence a larger dynamic range leads to larger step size and vice-versa.

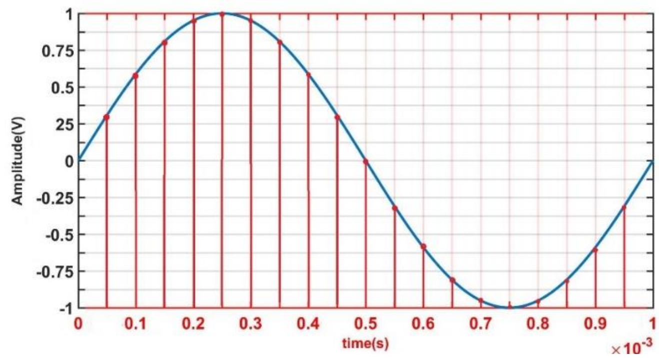

Figure 1. An analog signal with amplitude of 2 V peak to peak is observed on entire dynamic range of DSO and sampled at finite time interval

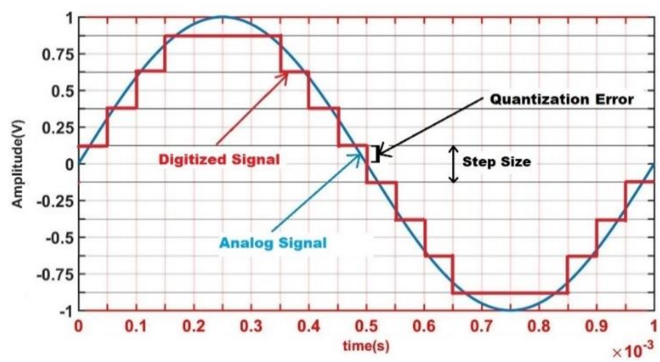

Figure 2. An analog signal observed in fig. 1 is quantized and digitized by DSO

To understand the effect of the dynamic range on the quantization noise, consider a sinusoidal waveform from a signal generator captured in a 3-bit DSO; hence the number of levels L used for quantization is $L=2^{n=3}=8$. In fig.1, a sinusoidal signal is plotted on a DSO in such a way that the dynamic range (amplitude scale) of DSO and dynamic range of the sinusoidal signal are the same. The digitized version of this sinusoidal signal is also plotted in fig. 2. Based on the sampling theory, the step size for the quantization is 0.25 V and the maximum quantization error ($Q_{max} = \Delta/2$) during the digitization process is 0.125 V in this case. Now, assume that the same sinusoidal wave is plotted on a DSO such a way that the dynamic range (amplitude scale) of DSO is twice the dynamic range of the sinusoidal signal; then the step size and the maximum quantization error during the digitization process is increased to 0.5 V and 0.25 V respectively. It is twice than the previous case. Therefore, it is clear that as the dynamic range of DSO increases then the quantization error is also increasing. So, to minimize the quantization error dynamic range of DSO should be kept at a minimal possible value.

III. Simulation Results

According to the sampling theory, the mean square quantization noise power is given by $\Delta^2/12$. Where Δ is the step size and it depends on the number of bits used for quantization.

The step size (Δ) is fixed for particular type of digital oscilloscope, irrespective of signal amplitude if the dynamic range is kept constant. To quantify the effect of quantization noise, a parameter called SQNR (signal to quantization noise ratio) is used usually. In case of the digital oscilloscope, if the signal is large enough to fit in dynamic range of DSO then SQNR is high but if signal is small compared to the dynamic range of DSO then SNRQ will be low. In the later case the effect of the quantization noise must be included in calculation of effective SNR.

Calculation of effective SNR:

Let us assume that the dynamic range of DSO is *Vd (-Vd/2 to Vd/2*) and the amplitude of a signal is A. The signal power (P) and step size (Δ) is given by,

$$P = \frac{A^2}{2} \tag{3.1}$$

$$\Delta = \frac{Vd}{L} \tag{3.2}$$

If $Nenv$ is random noise present in the environment and Nqn is quantization noise then the total noise ($Ntot$) is given by,

$$Ntot = Nenv + Nqn \tag{3.3}$$

The random noise power can be defined in terms of the signal power as follows,

$$Nenv = NF * P \tag{3.4}$$

Where, NF (Noise Fraction) is a constant and it is defined as a ratio of random noise power to signal power. If NF = 1 then SNR =1, NF < 1 then SNR >1 and NF > 1then SNR <1.

From eq. (3.1) and eq. (3.2),

$$Ntot = (NF * P) + \left(\Delta^2/12\right) \tag{3.5}$$

$$= NF * P + \left(\left(Vd/L\right)^2/12\right) \tag{3.6}$$

$$= \left(NF * \left(A^2/2\right)\right) + \left(Vd^2/(12 * 2^{2n})\right) \tag{3.7}$$

To represent the signal amplitude in terms of the dynamic range of the DSO, a parameter R can be defined as follow.

$$R = \frac{Dynamic\ range\ of\ the\ DSO}{Dynamic\ range\ of\ the\ input\ signal} \tag{3.8}$$

Then,

$$R = \frac{Vd}{2 * A} \tag{3.9}$$

and

$$A = \frac{Vd}{2 * R} \tag{3.10}$$

Then the eq. (3.7) is modified as follow,

$$Ntot = \left(NF * \left(Vd^2/8 * R^2\right)\right) + \left(Vd^2/(12 * 2^{2n})\right) \tag{3.7}$$

Then the effective SNR is given by,

$$SNReff = \frac{P}{Ntot} \tag{3.8}$$

From the eq. (3.1), (3.7) and (3.8),

$$SNReff = \frac{\left(Vd^2/8 * R^2\right)}{\left(NF * \left(Vd^2/8 * R^2\right)\right) + \left(Vd^2/(12 * 2^{2n})\right)} \tag{3.9}$$

$$SNReff = \left(\frac{\left(Vd^2/8 * R^2\right) * SNR}{\left(\left(Vd^2/8 * R^2\right)\right) + SNR * \left(Vd^2/(12 * 2^{2n})\right)}\right) \tag{3.10}$$

The above relations have been used to perform the MATLAB simulations to observe the dependency of SNR on the dynamic range of DSO, the number of bits (n) and background noise level. For simplicity, here we have used a sinusoidal wave as an information signal and instead of random noise, we have directly taken noise power in terms of NF (noise power normalized by signal power) for SNR calculation.

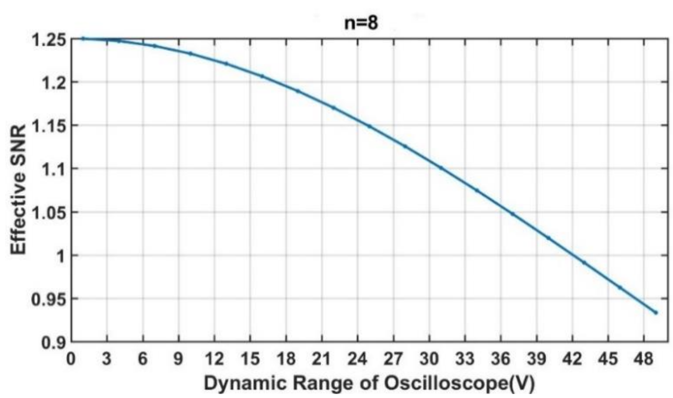

Figure 3. Total SNR Vs Dynamic range

In fig.3, SNR is plotted as a function of dynamic range (V) for a sinusoidal wave with an assumption of 8-bit quantization. It is assumed that original measured signal has NF = 0.8 (SNR = 1.25) and signal amplitude = 150 mV (V peak to peak = 300mv). From fig.3, it can be observed that effective SNR is decreasing by increasing the dynamic range of DSO.

In fig.4, effective SNR is plotted as a function of the original SNR of information signal for a fixed dynamic range of 50 V. It can be observed that effective SNR is always lower than the original SNR for a fixed dynamic range.

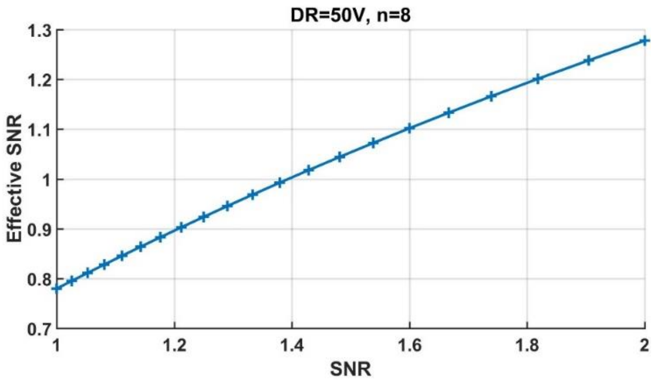

Figure 4. Effective SNR Vs original SNR

In fig. 5, for different values of quantization bits (n), SNR is plotted as a function of dynamic range for a fixed NF = 0.8 and Signal Amplitude = 150 mV. From the fig. 5, it can be observed that the gradient in SNR value with dynamic range is small if a higher number of bits are used for quantization.

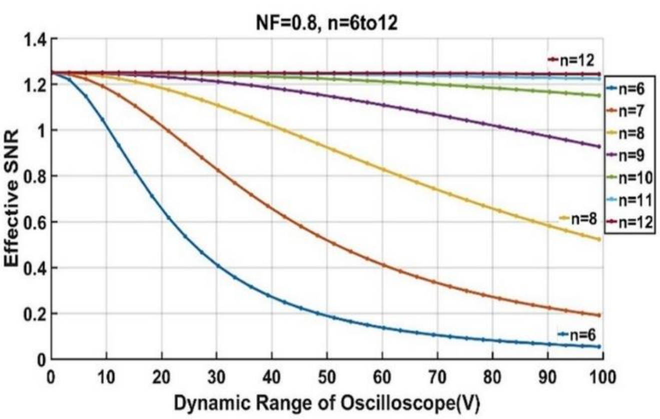

Figure 5. Effective SNR Vs Dynamic Range

In fig.6, for different values dynamic ranges, effective SNR is plotted as a function of original SNR by taking signal amplitude = 150 mV and assuming 8-bit quantization. From fig. 8, it can be observed that by increasing the original SNR, effective SNR increases more rapidly for smaller dynamic ranges compared to the larger ones.

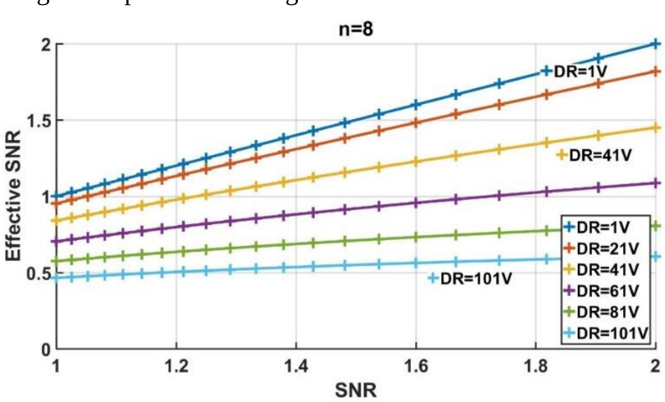

Figure 7. Effective SNR Vs Original SNR

The above results show the dependency of SNR on different parameters like the number of bits (n) used for quantization, the dynamic range of DSO and noise factor. As discussed in section 2, the number of bits (n) used for quantization and dynamic range of DSO are directly associated with quantization noise. Please note that the purpose of these simulations is limited to estimate some trends and to justify the effect of quantization noise on information signal only; more realistic data is presented in the next section.

IV. Experimental Results

The simulation results presented in the previous section describe the generalized case. In this section, we specifically focused on the Langmuir probe measurements. In the case of a Langmuir probe data, the entire I-V characteristic is distributed over a large dynamic range (generally 10's of V) corresponding

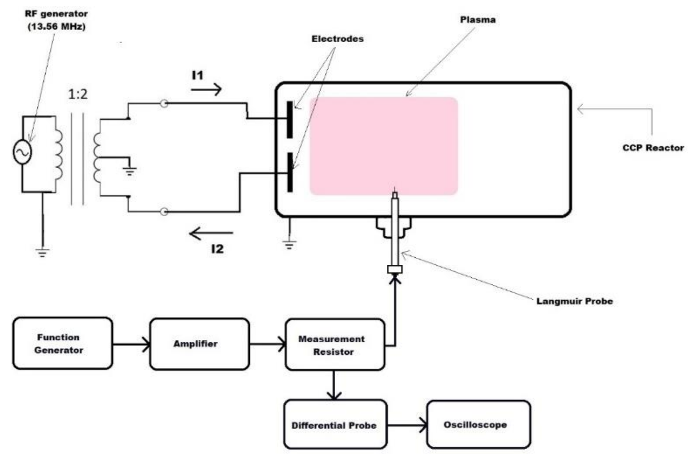

Figure 6. Experimental Setup

to electron current (few mA) to a few 10's of mV for the ion saturation current (few µA) across a current measuring resistor. Therefore, there is a large possibility of error in the measurement of ion saturation current due to quantization error in the oscilloscope.

As described in section 2, a measured signal may have a very small amplitude along with the random background noise. So, it is very difficult to get DC parameters because the random noise fluctuates very rapidly over the information signal. In this case, DC parameters are extracted by taking the mean value of the signal; but it is required to ensure that the mean value of the signal must be greater than the random variations, otherwise the mean value of a signal is dominated by random noise rather than the information signal.

In this section, an unusual trend is described; which is observed during the Langmuir probe plasma measurements. The entire I-V characteristics of the Langmuir probe generally capture by measuring the voltage drops across the measurement resistor for a range of biasing voltages. The measured voltage drops are eventually divided by the measurement resistor value to get the probe current.

The RF signal is fed to electrodes in push-pull configuration via impedance matching network for maximum power transfer.

The plasma measurement is performed using compensated Langmuir probe. The function generator [Agilent technology] generates the ramp voltage sweep and it is further amplified by an amplifier [Falco System], generated voltage sweep applies to compensated Langmuir probe via a small measurement resistor to capture the entire I-V characteristics. To measure the voltage drop across the measurement resistor (330 Ω), a differential probe was used. The output of the differential probe [SIGLENT DPB150] is applied to DSO, after that it can be stored for post-processing. The results presented in fig. 8 to 11 are taken by bias a compensated Langmuir probe with a fixed DC voltage and measuring the differential voltage across the measurement resistor.

The mean value of measure differential voltage vs. the dynamic range of oscilloscope is plotted in fig. 8. The corresponding SNR is also plotted as a function of dynamic range. These measurements were taken in a 9-bit oscilloscope [Tektronix TDS 3034C]. From fig. 8, it can be observed that the mean value of the measured signal is changing from 321 mV to

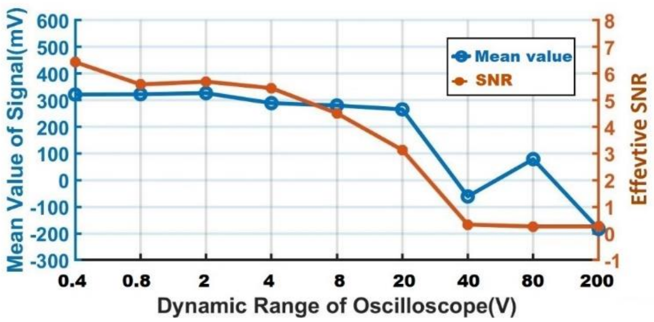

Figure 8. Measurement using 9-bit oscilloscope

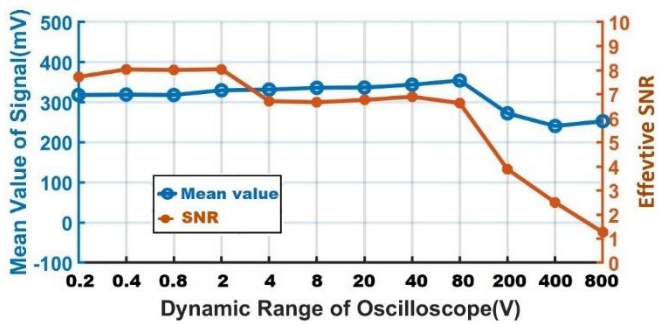

Figure 9. Measurement using 12-bit oscilloscope

265 mV when the dynamic range of the signal changes from 0.4 V to 20 V; corresponding SNR drops from 6.4 to nearly around 3. The dynamic range increase further than the mean value of a signal is drastically changed and it became a random value; it is obvious because SNR fall below the unity.

In fig. 9 & 10, the measurement results are presented for a 12-bit oscilloscope & 16-bit oscilloscope [Tektronix MSO58] respectively, for the same experimental condition described above. From fig. 9, the mean value varies from 318 mV to 252 mV when the dynamic range of the signal varies from 0.2 V to 800V; corresponding SNR drops from 8 to nearly around 1.2. In the case of a 9-bit oscilloscope, for the dynamic ranges beyond the 20 V, it is very difficult to get useful information; but in this case at 800 V of dynamic range, the SNR value still greater than the unity. Now, as shown in fig.10, SNR can be more than unity for a larger dynamic range than the above two cases, if measurement is taken using the 16-bit oscilloscope and for the 800V of dynamic range, SNR value is still greater than 3.

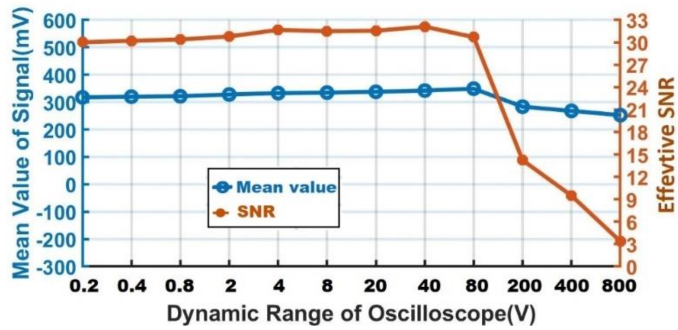

Figure 10. Measurement using 16-bit oscilloscope

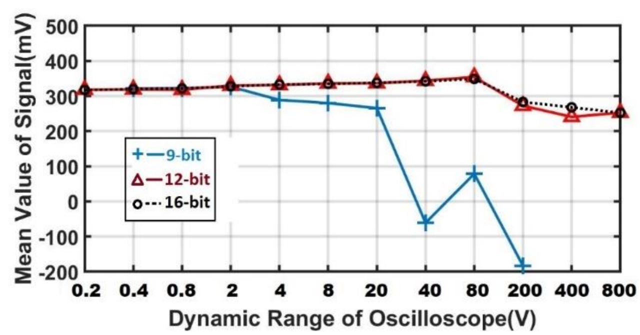

Figure 11. Mean value of measured signal vs. Dynamic range of DSO for different number of quantization bits

In fig. 11, for different quantization bits, measured signal plotted as a function of dynamic range. It can be observed that the mean value remains the same for 9-bit, 12-bit and 16-bit oscilloscope for a dynamic range of 2 V or less than it; if the dynamic range increase further then the measured signal of 9-bit oscilloscope starts to deviate from the other two signals and eventually becomes a random one. So, it is clear from fig. 11, the quantization noise will affect less for higher bit oscilloscope.

The typical I-V characteristic of the Langmuir probe measurement is presented in fig. 12. It is distributed over a large dynamic range. To measure the Plasma parameters accurately and minimize the quantization noise, a dynamic range of DSO is adjusted such a way that the signal can cover the entire dynamic range; but for a particular part of characteristics, dynamic range is very large as compared to information signal even though entire dynamic range I-V characteristic is same as the dynamic range of DSO; particularly for the ion-saturation part. The typical value of ion saturation current and electron saturation current is few μA and few mA respectively. So, a dynamic range of DSO needs to be set in the scale of mA. The current is in μA scale now measured on the mA scale; inherently the contribution of quantization ion-saturation inherently the contribution of quantization ion-saturation affects the accuracy of ion-saturation current.

In fig. 13, experimentally measured ion-saturation is plotted as a function of the dynamic range of DSO for a 9-bit oscilloscope. Please note that the original information is measured in voltage scale in form of differential voltage across measurement resistor; ion-saturation current is plotted after dividing it by measurement resistor value during the post-processing. It can be easily observed that ion saturation current changed gradually when the dynamic range changed from 40 mV to 1600mV; for dynamic range beyond the 1600mV, there is a drastic change in the ion-saturation current. The change in ion-saturation at 1600mV dynamic range is around 28% from its value at 40mV dynamic range and it is around 450% in the case of 4000mV dynamic range. The dynamic range is increases further than it is impossible to detect the ion-saturation current. In other words, useful information is vanished due to the quantization noise for dynamic range beyond 4000mV.

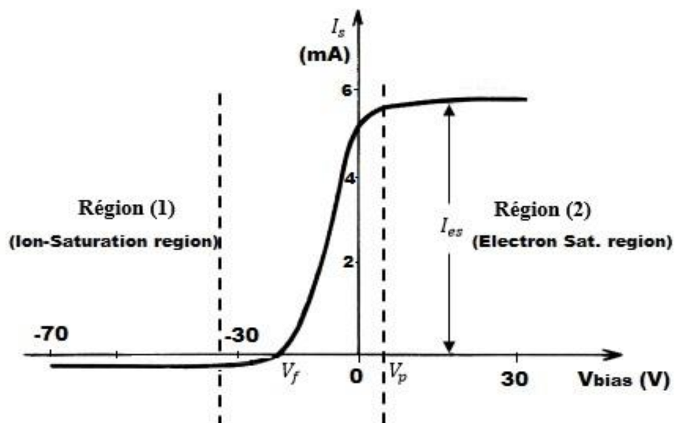

Figure 12. Typical I-V characteristics of Langmuir probe

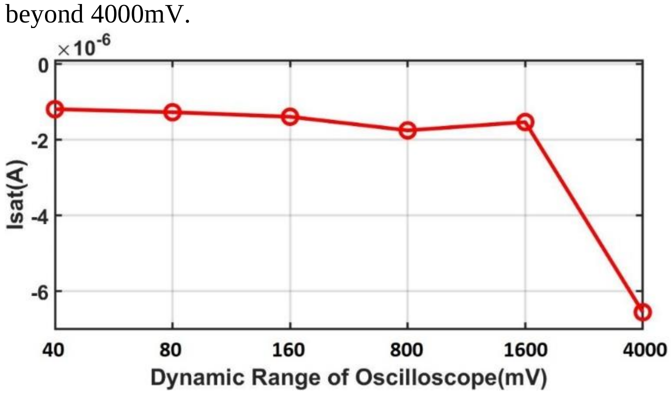

Figure 13. Ion-saturation current vs. dynamic range of DSO

V. Recommendation

The SNR value of the information signal is small and measurements are done through DSO, then due to quantization noise SNR value can fall below unity and information cannot be reliable. So, the accuracy of measurement primarily depends on the background noise level and quantization noise. The quantization noise depends on the step size. It is clear that step size must be small to minimize the quantization noise. To avoid the false detection of Plasma parameters, the signal amplitude must be greater than the total noise amplitude; in the case of the DC measurement, the mean value of a signal must be greater than the total noise amplitude.

$$S > \max\{(S - Nmin), (Nmax - S)\} + \left(\frac{\Delta}{2}\right) \qquad (5.1)$$

Where, S is the mean value of DC signal, Nmax is Maximum noise amplitude and Nmin is Minimum noise amplitude.

$$S > N' + \left(\frac{\Delta}{2}\right) \qquad (5.2)$$

Where, $N' = \max\{(S - Nmin), (Nmax - S)\}$

The eq. (5.2) can be modified in terms of the dynamic range of the oscilloscope. To avoid the false detection of the Plasma parameters, the authors recommend that the maximum dynamic range to be limited to the following relation.

$$DR < 2^{n+1} * (S - N') \qquad (5.3)$$

VI. Conclusion

The errors associated with the Langmuir probe plasma measurements are subject to both quantization error and background noise. The accurate measurement of Plasma parameters is very difficult if quantization noise reduces the original SNR value; it is almost impossible to get true information from measured data when SNR falls below the unity. The modified formula of SNR is presented in this paper to consider the effect of the quantization noise. The work reported in this paper is important because it shows the dependency of effective SNR on the dynamic range of DSO, which is very important for the accuracy of plasma parameters. The accuracy of ion-saturation current measurement as a function of dynamic range is also reported. It proves that when the dynamic range of DSO exceeds certain limits, as step size increases, inherently the contribution of quantization is tremendous and it is almost impossible to extract plasma parameters from measured data. To avoid this measurement difficulty, the recommendation given by authors in section 5 can be followed to acquire meaningful data.

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