$1/f$ Noise Model of 980 nm InGaAs/GaAs Laser Diodes based on Parasitic Parameters under Low Injection Current

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***Abstract*—It is found that low frequency noise is always as a fast, easy-to-use, accurate and non-destructive tool to characterize the performance and the reliability of materials and electrical devices. In this paper, the noise equivalent circuit of laser diode with parasitic parameters under low injection current is developed. Based on theory of the carrier number fluctuation, $1/f$ noise model in 980 nm InGaAs/GaAs laser diode under low injection current is developed. This model suggests the low frequency noise of the device is caused by the fluctuation of surface nonradiative recombination current, which depends on the surface oxide traps and lattice dislocation. The low injection current were performed from one-thirtieth up to very close to the threshold current. The model can explain well the experimental results.**

***Index Terms*—$1/f$ noise model, laser diodes, low injection current, nonradiative recombination current, parastitic parameters**

I. INTRODUCTION

980 nm InGaAs/GaAs laser diodes (LD) have been widely utilized in a plurality of fields, such as optical fiber communication, laser processing, assembly industrial and many other applications due to their high output power, stable optical spectrum, high photoelectric transformation efficiency, low electrical consumption, high performance and potential low-cost [1], in which area, high quality and functional reliability are required. As optical devices become more widely used and the performance requirements gradually improved, their reliability issues are of concern. Low frequency noise is always a fast, easy-to-use, accurate and non-destructive tool to characterize the performance and the materials and electrical devices. Low frequency $1/f$ noise, also as known as flicker noise, depends on the defects and impurity concentrations in the microscopic structure of the device to reflect the inherent quality and reliability of the device [2]. So, research on low frequency noise characteristics of laser diodes is of great significance.

The $1/f$ noise characteristics in laser didoes has been investigated for many years by many researchers and different $1/f$ noise models of semiconductor laser diodes have been developed and tried to explain the physical mechanism and the origins of $1/f$ noise [3]. In the below-threshold region the characteristics of the active region dominate the electrical behavior of the LD. However, comparison of the I-V characteristics of the LDs, the low frequency $1/f$ noise characteristics under low injection current contain more microscopic information that can reflects the internal defects of the device. Meanwhile, processes, observed at the low injection current (below laser diode threshold), could be used as precursors of device quality and degradation mechanism which affects LD reliability [4].

In the present paper, a $1/f$ noise model in 980 nm InGaAs/GaAs laser diodes under low injection current is presented, which takes into account the effects of parasitic parameters and nonradiative recombination. the noise equivalent circuit model of laser diodes with parasitic parameters which includes the parameters of package part, laser chip part and the active region of LD is developed. This noise equivalent circuit model is derived from the semiconductor physics and the electrical characteristics of LD. According to the noise theory (mainly the mobility fluctuation model and the carrier number fluctuation model), the recombination $1/f$ noise model based on parasitic parameters in the package surface and active region of LD under low injection current will also be described.

II. DEVICE DETAILS AND EXPERIMENTAL ANALYSIS

A. The device details

The device used is InGaAs/GaAs MQW high-power laser diodes lasing at 980 nm. The device structure was grown by means of metalorganic chemical vapor deposition (MOCVD) on a GaAs substrate and consisted of the active layer using an InGaAs double quantum well structure with two InGaAs well layers about 7-9 nm, and 100 nm composition AlGaAs barrier layer between the wells about 100 nm. In order to improve the anti-COD of the device, a 2.1μm ultra-large cavity waveguide layer is adopted, in which the waveguide layer and cladding layer are $\mathrm{Al}_{0.1}\mathrm{Ga}_{0.9}\mathrm{As}$ and $\mathrm{Al}_{0.3}\mathrm{Ga}_{0.7}\mathrm{As}$, respectively. The waveguide layer is asymmetric, that is the thickness of the layer is 300nm lager than the thickness of the upper waveguide layer to reduce the loss of the waveguide layer and suppress the higher-order mode. After the epitaxial growth, wide strip ridge device is fabricated by first etching a ridged plate with 300 nm height, sputtering 200 nm of SiO_2 and forming a 95μm p-type electron hole by photoetching, using Ti/Au as p-type electrode and AuGeNi/Au as n-type electrode. The cavity length of the chip cleavage is 400μm, and the stripe width is 95μm. The threshold current and the slope efficiency were about 700 mA and 1.12 W/A at 25 °C.

B. Noise analysis of laser diode under low injection current

In order to investigate the noise source of the laser diode and its $1/f$ noise source under low injection current, a noise equivalent circuit of 980 nm InGaAs/GaAs laser diodes with parasitic parameters under low injection current according to the low frequency noise analysis methods of Van der Ziel, Harder et al. is established. This circuit model can provide useful information for establishment of the laser diode $1/f$ noise model under low injection current (below threshold). The noise equivalent circuit model is shown in Fig.1. This model is a two-port electrical network and consists of two parts i.e. LD parasitic parameter part and active region parameter part, of which LD parasitic parameter part includes LD chip parasitic parameters and package parasitic parameters. The meaning of the parameters and formula derivation in the noise equivalent circuit will be described in detail in the subsequent paper [5].

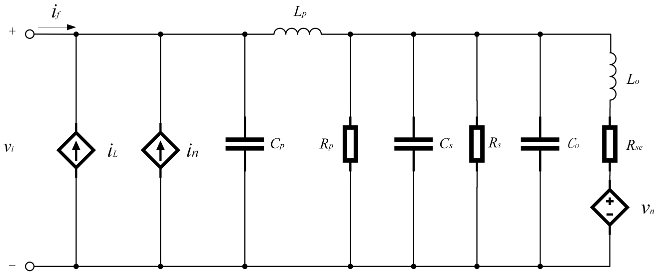

Fig. 1. the noise equivalent circuit model with parasitic parameters under low injection current

III. $1/f$ NOISE MODEL OF 980 NM INGAAS/GAAS LASER DIODES UNDER LOW INJECTION CURRENT

Semiconductor laser diode is a type of laser with semiconductor material as optical gain medium, which is excited by p-n junction injection current to generate stimulated emission in a chip and establish optical oscillation, thus produce laser. In the present paper, the laser diode is restricted to below-threshold (under low injection current) operation and stimulated emission is therefore neglected.

In general, the surface of laser diode has a certain modulation effect on its performance, the $1/f$ noise of laser diode depends on the surface composition of its operation current. In general, the current through the laser diodes generally has radiative recombination current I_r and the surface recombination current I_{nr} which is generated by the non-radiative recombination. Current-voltage characteristics in the low bias range are governed by the surface non-radiative recombination current if p-n junction reaches the surface [6]. Therefore, under low injection current, the low frequency noise of laser diode mainly comes from $1/f$ noise caused by the fluctuation of surface non-radiative recombination current, which has a similar mechanism and a good corresponding relationship with the surface non-radiative recombination current.

When the LDs is under forward bias, the difference between the energy quasi-Fermi level of electrons E_{Fn} and the quasi-Fermi level of holes E_{Fp} is related to [7]

$$E_{Fn} - E_{Fp} = qV_j \tag{1}$$

where q is the electron charge, and V_j is diode junction voltage.

The carrier concentrations in the space charge region are given by

$$n(x) = n_i \ \exp\left(\frac{E_{Fn} - E_{ix}}{k_0 T}\right) \tag{2}$$

$$p(x) = n_i \ \exp\left(\frac{E_{ix} - E_{Fp}}{k_0 T}\right) \tag{3}$$

where E_{ix} is the intrinsic Fermi level in the space region. n_i is the intrinsic carrier concentration. k_0 is the Boltzmann constant. T is the absolute temperature.

At the edge of the space charge region, the non-equilibrium minority concentrations of the p side pp' and the n side nn' are respectively

$$n_p = n_{p0} \ \exp\left(\frac{qV_j}{k_0 T}\right) = n_{n0} \ \exp\left(\frac{qV_j - qV_D}{k_0 T}\right) \tag{4}$$

$$n_n = n_{n0} \ \exp\left(\frac{qV_j}{k_0 T}\right) = p_{p0} \ \exp\left(\frac{qV_j - qV_D}{k_0 T}\right) \tag{5}$$

where n_{p0}, p_{p0} are the equilibrium carrier concentrations of p region, and n_{n0}, p_{n0} are the equilibrium carrier concentrations of n region, respectively. V_D is barrier potential of $p - n$ junction.

The carrier concentrations in p region and n region are given by the following equations:

$$P_p = N_A = n_i \exp\left(\frac{V_{Fp}}{V_T}\right) \tag{6}$$

$$n_n = N_D = n_i \exp\left(\frac{V_{Fn}}{V_T}\right) \tag{7}$$

From eqn. 1, the diode junction voltage can be written as

$$V_j = \frac{1}{q}(E_{Fn} - E_{Fp}) = \frac{k_0 T}{q} \ln(\frac{n_{n0}}{n_{p0}}) = \frac{k_0 T}{q} \ln(\frac{N_D N_A}{n_i^2}) \tag{8}$$

According to the equation above, the quasi-Fermi potential for electrons $V_{Fn} = \frac{k_0 T}{q} \ln\left(\frac{N_D}{n_i}\right)$,and the quasi-Fermi potential for holes is $V_{Fp} = \frac{k_0 T}{q} \ln\left(\frac{n_i}{N_A}\right)$.$N_D N_A$ are doping concentrations.

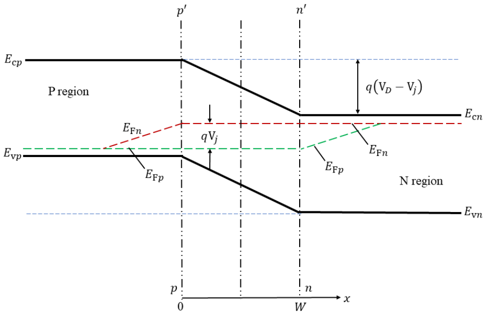

Fig. 2. Energy band diagram of p-n junction under forward bias

From the reference, we can define the intrinsic Fermi level for the intrinsicE_{io} as zero. From the energy band diagram of p-n junction under forward bias (shown in Fig. 2), the intrinsic Fermi level can be described approximately [7]:

$$E_{ix} = \frac{E_{i0} - E_{iW}}{-W} \cdot x = \frac{q\left(V_j - V_{Fn} - V_D\right)}{W} x \tag{9}$$

where the origin of the x axis is set at the p side of the space region. W is the total width of the space charge region, and the value range is $[0, W]$.

Under low and forward injection current, a part of the injected electron and hole is confined as a minority carrier at its quantized ground state within the surface space charge region. Each minority carrier diffuses along the surface in the cladding layer until the recombination takes place, where recombination rate is determined by the surface recombination velocity across section, etc [8]. This same analysis can also be applied to the interface of the investigated laser diodes, so the recombination current per unit length under low injection current at the interface of space charge region can be expressed by the following equation:

$$I_r = qA\int_0^W U dx = qA\int_0^W s \cdot \frac{n_s p_s - n_i^2}{n_s + p_s + 2n_i} dx \tag{10}$$

where U is the recombination rate of carriers through the recombination center, and A is the cross section. $s = v_{th}\sigma_s N_{it}$ is the surface recombination velocity. v_{th} is the electron thermal velocity, σ_s is the trap cross section and N_{it} is interface trap density. n_s is the surface electron concentration, and p_s is the surface hole concentration.

The diode current arises from nonradiative recombination along the stripe edges and at the heterointerface under low bias [9]. It is assumed that the nonradiative recombination rate is proportional to the electron density n, and is characterized by a nonradiative carrier lifetime τ_{nr}. The nonradiative recombination rate r_n is given by:

$$r_n = \frac{n}{\tau_{nr}} \tag{11}$$

The laser diode non-radiative recombination current I_{nr} is obtained by multiplying r_n by the recombination current under low injection current I_r:

$$I_{nr} = r_n qA\int_0^W S \cdot \frac{n_s p_s - n_i^2}{n_s + p_s + 2n_i} dx \tag{12}$$

The carrier concentrations at the surface of the space charge region can be written by

$$n_s = n(x)\exp\left(\frac{V_s}{k_0 T}\right) = n_i \exp\left[\frac{q\left(V_j + V_s - V_D\right)}{k_0 T} - q\frac{V_j + V_{Fp}}{W}x\right] \tag{13}$$

$$p_s = n(x)\exp\left(-\frac{V_s}{k_0 T}\right) = n_i \exp\left[q\frac{V_j + V_{Fp}}{W}x - \frac{q\left(V_{Fp} + V_s\right)}{k_0 T}\right] \tag{14}$$

where V_s is the surface potential of diode.

According to eqn. 10, the surface recombination rate can be expressed by

$$U(x) = s\frac{n_s p_s - n_i^2}{n_s + p_s + 2n_i} \tag{15}$$

Substituting eqn. 13 and eqn.14 into eqn.15 is written by

$$U(x) \approx \frac{1}{2} s n_i \frac{\exp\left(\frac{qV_j}{k_0 T}\right)}{\cosh\left[\frac{q}{k_0 T}\left(V_j + V_{Fp} + \frac{V_S}{2}\right) - q\frac{V_j + V_{Fp}}{W}x\right]} \tag{16}$$

Substituting eqn. 16 into eqn. 12, the diode nonradiative recombination current at the surface of the space charge region can be expressed by

$$I_{nr} = \frac{1}{2} r_n qA v_{th}\sigma_s N_{it} n_i \exp\left(\frac{qV_j}{k_0 T}\right)\left(\frac{k_0 T}{q}\right)\left(\frac{W}{V_j + V_{Fp}}\right) \cdot \gamma \tag{17}$$

where $\gamma = \mathrm{acrtan}\left\{\exp\left[\frac{q}{k_0 T}\left(V_j + V_{Fp} + \frac{V_s}{2}\right) - q\frac{V_j + V_{Fp}}{W}x\right]\right\}\Big|_0^W$

For the laser diodes operating under low injection current, the low frequency noise of the device is caused by the fluctuation of surface nonradiative recombination current, which depends on the surface oxide traps density and lattice dislocation. At the same time, the surface defects, impurities, dislocations and other factors of LDs cause the surface nonradiative recombination current. It can be seen that $1/f$ noise has a similar mechanism to the surface recombination current. Therefore, we relate the $1/f$ noise of laser diode under low injection current to the fluctuation of the surface nonradiative recombination current. According to eqn.17, the fluctuation of the surface nonradiative recombination current is given by

$$\frac{\delta I_{nr}}{I_{nr}} = \frac{q}{k_0 T}\frac{\delta N_{ot}}{A N_{ot}} \tag{18}$$

According to eqn.18, the $1/f$ noise spectral density of the surface nonradiative recombination current can be written by

$$S_{I_{nr}}(f) = I_{nr}^2\left(\frac{q}{k_0 T}\frac{1}{A N_{ot}}\right)^2 S_{N_{ot}} \tag{19}$$

Where $S_{N_{ot}}$ is the oxide-trapped charge spectral density, which can be given by

$$S_{N_{ot}} = \frac{q^2 k_0 T N_t \lambda}{f} \tag{20}$$

whereN_t is the number of oxide-trapped charge per unit per unit energy $(/eV/cm^3)$, λ is the attenuation tunneling distance.

The $1/f$ noise spectral density of the surface nonradiative recombination current can be expressed by

$$S_{I_{nr}}(f) = I_{nr}^2 \frac{q^4 N_t \lambda}{k_0 T A^2 N_{ot}^2 f} \tag{21}$$

IV. RESULTS AND DISCUSSION

Fig.3 show the surface nonradiative recombination current power spectral density $S_{I_{nr}}(f)$ of a typical LD sample at five different low injection currents, which is 20.50mA, 255mA, 385mA and 530mA, respectively. It shows that the $1/f$ noise PSD of the sample increases with the injection current. In Fig. 4. shows the magnitude (B) of $1/f$ noise PSD versus the injection current below threshold.

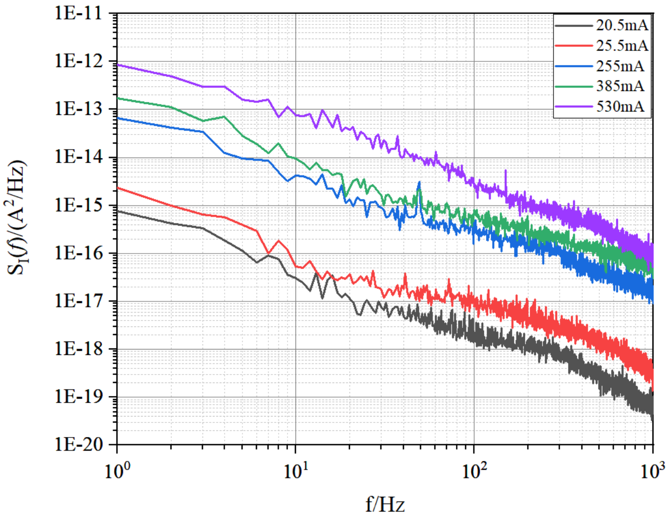

Fig. 3. The $1/f$ noise PSD under different injection current

Equation (22) shows that the oxide-trapped charges lead to a decrease in the surface nonradiative recombination current noise.

The surface recombination velocity increases with the induced interface states, which can bring about an increase in surface nonradiative recombination current. $1/f$ noise of InGaAs/GaAs laser diode is due to an increase in surface recombination velocity and it moderated by oxide charges. The cavity quality of the laser diode can be evaluated by measuring the low frequency noise of the device under low injection current.

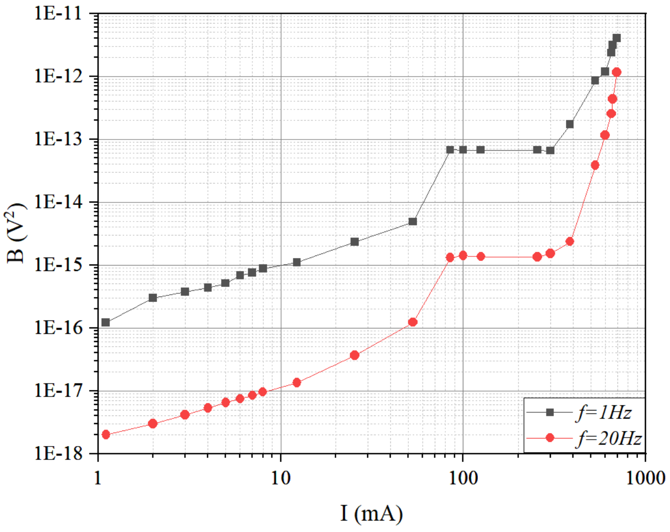

Fig. 4. The magnitude (B) vs injection current below threshold

V. CONCLUSIONS

In this paper, it is thought that the fluctuation of the surface nonradiative recombination current of 980 nm InGaAs/GaAs laser diode under low injection current causes the $1/f$ noise. A noise equivalent circuit model with parasitic parameters under low injection current is developed which identifies the parameters and describes the source and composition of noise. Based on the theory of carrier number fluctuation and the model of surface nonradiative recombination current, $1/f$ noise model is developed. The model can explain well the experimental result.

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