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PHYSICS OF SEMICONDUCTOR DEVICES

Picosecond Internal *Q*-switching Mode Correlates with Laser Diode Breakdown Voltage[1]

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Abstract—The record picosecond power density recently achieved with a current-pumped laser diode turned our attention to a still unexplained 50-year-old phenomenon termed "internal *Q*-switching". The correlation found experimentally here between the relatively high breakdown voltage (~5–11 V) in a heavily doped single-heterostructure laser diode and its high-power picosecond lasing provides a means for solving the puzzle. Together with the experimental fact that picosecond lasing occurs from the *p–n* junction, this implies that internal *Q*-switching is determined by the compensated layer rather than by "traditional" single-heterostructure waveguide. This finding is valid for various growth technologies independently of whether the high breakdown voltage and picosecond lasing are achieved by exact compensation of shallow donors by shallow acceptors, or by doping profile gradients.

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1. INTRODUCTION

High-power picosecond single optical pulses generated with directly current-pumped laser diodes are of practical importance in applications where cost efficiency and miniaturization are required, e.g. in high-precision laser radars [1] and 3D time-imaging.

The first heterojunction diode lasers were single-hete rojunction (SH) lasers based on heavily doped n^+, p^+ GaAs and p^+ AlGaAs layers grown by liquid phase epitaxy (LPE) in the 1960s. Researchers were surprised by the extremely long, nanosecond range, lasing delays above a critical temperature [2] and termed the phenomenon "internal *Q*-switching" in SH laser diodes (see [2], ref. 23),which means that lasing takes place only at the end of the current pulse independently of the current pulse duration. A supplementary factor was the observation of a "spiking mode" in the internal *Q*-switching mode (see [2], ref. 24), which later provided a means for demonstrating unique high-power picosecond pulses (100 W/35 ps FWHM/150 μm stripe width) [3, 4]. This is highly attractive in applications due to the simple laser diode structure and simple nanosecond current driver based on a commercial silicon avalanche transistor, but it lacks understanding of the physical mode of operation. In particular, it has not been clear until now why some heavily doped SH lasers demonstrate high-power picosecond *Q*-switching while others do not, even though the structures look the same at first glance. Multiple attempts [5, and references therein] at giving a comprehensive interpretation of the long delay and the internal *Q*-switching mode, e.g. light reabsorption models [2], have apparently failed. The most popular model, that of F. D. Nunes dealing with SH waveguide destruction [5], explained a different phenomenon that is not related to high-power picosecond lasing [6], and does not in any case provide an interpretation of the experimental fact that picosecond lasing occurs from the *p–n* junction [7, 8] and not from the recovered SH waveguide.

Even though the internal *Q*-switching phenomenon applies to old-fashioned SH laser diodes, the production of which has now ceased, the physical explanation of the picosecond mode has remained an open question. Therefore an obvious practical motive exists for returning to this problem, using state-of-the-art, well reproducible metal-organic chemical vapor deposition (MOCVD) instead of LPE, which suffers from control and reproducibility problems. "There are no competitive methods which achieve such stable, high-power picosecond pulses by so simple means as internal Q-switching in SH lasers provides." This nevertheless needs an understanding of which structural parameters of heavily doped SH lasers are responsible for picosecond operation. We believe that the profound correlation demonstrated in this work will provide the basis for a breakthrough with regard to this problem, giving good chances of interpreting the phenomenon, or at least localizing the main structural parameters responsible for picosecond operation, and

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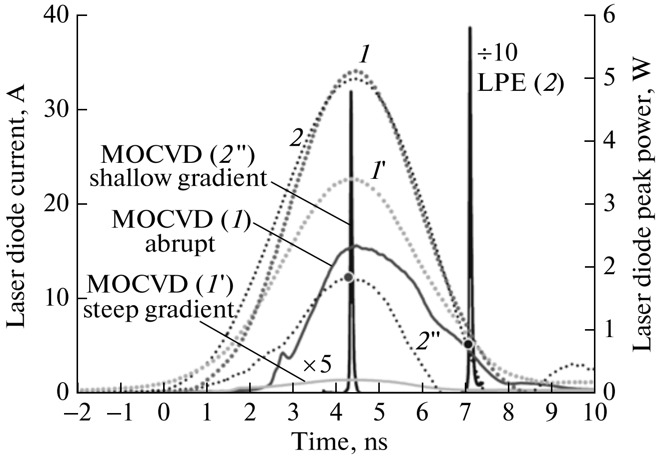

Fig. 1. Pumping current and optical response of SH laser diodes grown by different methods: *1*—MOCVD with an abrupt *p*–*n* junction, *1*'—MOCVD with a steep gradient, *2*—LPE, *2*"—MOCVD with a shallow gradient.

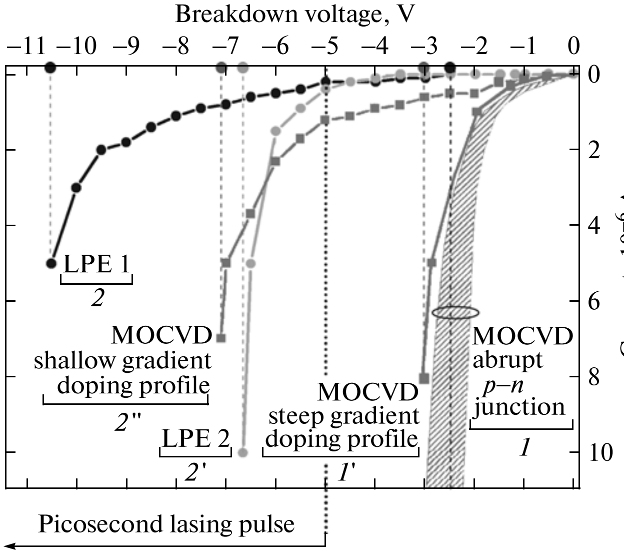

Fig. 2. *I*–*V* characteristics of the diodes. Curve numbers correspond to those in Fig. 1 with one feature: (*2*) LPE growth on a p^+ substrate (LD-60, Laser Diode Inc., USA), and (*2*') LPE growth on a n^+ substrate (Inject Enterprise, Saratov, Russia).

for creating an empirically well optimized and reliable picosecond laser diode. We think that the correlation shown below between high breakdown voltage and the ability to operate in high-power picosecond mode means that the compensated layer around the *p*–*n* junction plays a dominant role in the regime of interest.

2. LONG LASING DELAY AND INTERNAL Q-SWITCHING

Figure 1 shows the pumping current pulses and corresponding optical responses of different SH laser diodes based on roughly the same structure, i.e., having heavily doped layers: p^+(AlGaAs)–p^+(GaAs)–n^+(GaAs). The aluminium composition of the heteroinjector is apparently comparable between diodes, and the heavily doped (~(2–4) × 10^{18} cm^{-3}) "active" p^+(GaAs) layer is of comparable thickness (~2–3 μm) in all diodes. Laser behavior can be clearly separated into two groups. Diodes belonging to first group (curves *1* and *1*') demonstrate only quasi-steady-state lasing with a moderate (<1–2 ns) delay, and no picosecond mode can be achieved at any current amplitude or lattice temperature. Lasing occurs from the "active" p^+-GaAs layer in all these lasers. The second group (curves *2* and *2*") shows picosecond range (~20–50 ps FWHM) optical pulses within a relatively wide range of current pulse amplitudes and lattice temperatures (>300 K). Well pronounced in the second group is an experimentally observed spatial location of the lasing mode around the *p*–*n* junction (with a possible sub-micron shift towards the n^+ or p^+ layer). Numerous growth experiments [8] using MOCVD technology have been focused on varying the doping concentration and layer thickness in the p^+ and n^+ layers with the aim of finding the parameter(s) responsible for this picosecond lasing. At last we noticed an unexpected correlation with the breakdown voltage (see Fig. 2), which was valid for all the diodes investigated. First of all, all lasers with a breakdown voltage ≤3 V (curves *1* in Fig. 2), corresponding to *p*–*n* junctions with a doping level >10^{18} cm^{-3}, have shown only quasi-steady-state behavior. Then, checking "old" LPE diodes which demonstrated picosecond *Q*-switching lasing in 100% of cases, we found that all of them had a surprisingly high breakdown voltage ~(7–11) V (curves *2* and *2*' in Fig. 2), corresponding to a net doping concentration of only ~10^{17} cm^{-3}, even though we know a priori that the actual concentration of the acceptors and donors was ~(2–4) × 10^{18} cm^{-3}. No other explanation exists for this other than a very high compensation degree (only a few percent of non-compensated impurities, which is apparently intrinsic to this particular growing regime). Together with the fact of picosecond emission from the *p*–*n* junction, this clearly suggests that the region around the *p*–*n* junction is responsible for the *Q*-switching behavior. Unfortunately, the MOCVD method does not allow such an exact compensation to be achieved reproducibly, and so we based our further experiments on the use of a gradual reduction in the acceptor and donor densities towards the *p*–*n* junction. The results for steep gradient profiles (linear reduction from 4 × 10^{18} to ~ 6 × 10^{16} cm^{-3} within 0.5 μm) are represented by curves *1*' in Figs. 1 and 2, and those for shallow gradient profiles (linear reduction from 4 × 10^{18} to ~ 8 × 10^{16} cm^{-3} within 3.5 μm) by curves *2*".One can see that the same correlation takes place (high breakdown voltage—picosecond lasing) despite the significant change in the structure and technology. Also, the same correlation is still valid for two different LPE methods (different substrate types, n^+ or p^+, produced by different companies in different countries), see curves *2* and *2*'.

3. CONCLUSIONS

The correlation found here between picosecond lasing and breakdown voltage when the latter is elevated by acceptor-donor compensation speaks in favour the compensated layer being responsible for internal *Q*-switching behavior. Independent of whether *Q*-switching is determined by waveguide mechanisms such as gain-guiding [9] or by peculiarities in temporal/spectral/spatial absorption associated with the Burstein—Moss shift [10], this observation is of considerable significance for picosecond laser development and could help in interpreting this complicated phenomenon.

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