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Q switching of low-threshold buried-heterostructure diode lasers at 10 GHz

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bunched together and the standard deviation of the clusters in the plateau region is about 0.008. This value is also achieved after the film was stressed for 10 days in a humidity chamber set to 65 °C and 75% relative humidity (RH). This should be compared to the measured standard deviation of 0.04 for pure Te and 0.025 for a $Te_{72}Se_{28}$ alloy; both samples were stressed at the above conditions. Only TeN_x survived prolonged chemical stress in a KOH 1-molar solution.

Environmental and chemical stress tests revealed that the TeN_x films can withstand prolonged attack. It is not obvious why the TeN_x films are (i) more sensitive and (ii) chemically stable. To understand the intrinsic properties, one has to consider that these films are produced in a reactive plasma. It is assumed that at small N_2 partial pressure only a small amount of atomic nitrogen is chemically incorporated into the network. These nitrogen sites can terminate Te chains and cross-link chains and Te rings. Such bonding might make the network resistant against oxidation or corrosion, consistent with the results of the rapid stress tests.

The ablation mechanism in Te alloys has been studied extensively.[7–9] Why should nitrogen incorporation make the TeN_x films more sensitive for ablative optical recording? The ablation process can be viewed as a two-stage mechanism: (1) melting and initialization of ablation and (2) final hole formation determined by the counteraction of the surface tension of the melt and the capillary force. A more sensitive film must have a trigger mechanism built in for earlier and easier hole opening. This might be accomplished in the melt by partial decomposition and succeeding evolution of N_2 gas, which would certainly produce a mechanical force for hole initialization.

In conclusion, a series of TeN_x compounds has been made by reactive sputtering using an Ar-N_2 gas mixture. Good hole formation and threshold characteristics: a twofold increase in sensitivity and a flat plateau, have been observed. Furthermore, these Te nitrides are resistant against severe environmental and chemical stress conditions.

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Q switching of low-threshold buried-heterostructure diode lasers at 10 GHz

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Buried-heterostructure actively *Q*-switched diode lasers have been made with threshold currents as low as 14 mA. The lasers operate continuously at room temperature. Modulation has been observed at rates up to 10.5 GHz. Evidence of several modes of *Q* switching has been obtained.

Q-switched diode lasers are of interest for high-bandwidth optical fiber communication systems.[1–5] Laser pulses at modulation rates of several tens of gigahertz should be possible.[5] Previously reported actively *Q*-switched semiconductor lasers with an integrated electroabsorption modulator have been operated on a pulsed basis with thresholds of 240 mA.[3,5] A two-section buried-heterostructure laser with a proton-isolated modulator was also reported.[6] These devices had a threshold of about 40 mA and were *Q* switched at 3 GHz. Here, we report buried-heterostructure *Q*-switched lasers[7] with thresholds as low as 14 mA at an emission wavelength of 1.3 μm. The capacitance of the intracavity electroabsorption modulator can be as low as 0.1 pF under reverse bias. Since the capacitance is small and only a few volts of reverse bias are required, the laser can be easily modulated when integrated with low-power high-speed transistors without the high current drive required for direct-current modulation. The devices have been continuously operated with full on/off modulation at rates of at least 10 GHz.

The design, fabrication, and operation of the laser are similar to the zinc-diffused stripe *Q*-switched lasers reported earlier[3,5] except for modifications made to incorporate the buried heterostructure. The laser is fabricated from a double-heterostructure wafer consisting of a 2×10^{18} cm^{-3} Sn-doped buffer layer, a 1×10^{16} cm^{-3} *n*-type $Ga_{0.26}In_{0.74}As_{0.60}P_{0.40}$ active layer, and a 1×10^{16} cm^{-3} *n*-type InP cap layer. Both selective chemical etching to define an active region about 2 μm wide and a mass transport process[8] to bury the active region are used to form the buried heterostructure. Zinc is selectively diffused to form an amplifier section and beryllium is selectively implanted to form a modulator section as shown in Fig. 1. Au-Zn contacts are applied to the *p*-type regions and a Au-Sn contact is applied to the *n*-type substrate. Mirrors are formed by cleaving. The amplifier is forward biased to produce optical gain while the modulator is reverse biased to produce optical loss. The modulator design is based on the use of electroabsorption (Franz–Keldysh effect). For optical energies slightly less

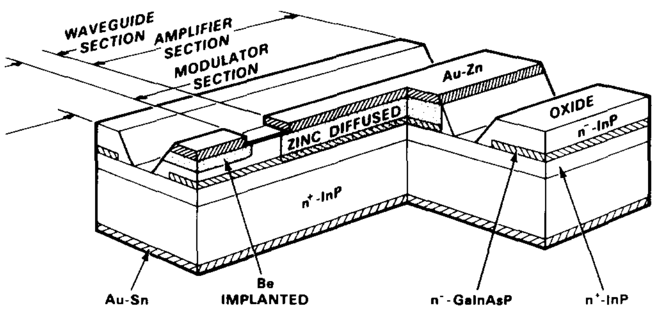

FIG. 1. Perspective cutaway view of the Q-switched laser. The buried-heterostructure active region extends through all three sections of the device.

than the band gap of the GaInAsP layer, the optical absorption can be controlled by the electric field produced in the modulator *pn* junction. The bulk absorption in the GaInAsP layer can be increased from a very small value to over 1000 cm^{-1} as the electric field is varied from zero to $>3.6\times10^5$ V/cm for photon energies as much as 60 meV below the energy gap.[9] The amplifier and modulator are optically coupled but electrically isolated by the waveguide section. The cross section of the buried heterostructure is constant throughout the device. The active region is about 0.2 μm thick and 2 μm wide. The position of the beryllium-implanted junction is deliberately offset from the quaternary layer as shown in Fig. 1 to prevent electroabsorption at zero bias.[3] Typically the length of the amplifier is 150–250 μm while the length of the modulator is 25–75 μm. The waveguide section is 25 μm long.

The laser is mounted in a package between two microstriplines which bring the electrical drive signals to the two sections. In order to facilitate bonding, the device is mounted with the substrate side soldered to the heatsink.

The lasers have thresholds as low as 14 mA with the modulator open circuited. The low threshold of the lasers permits continuous operation at room temperature. In order to characterize the modulator loss, the threshold of the laser can be measured as a function of the modulator reverse bias. At a 13-V reverse bias the pulsed threshold for one device (Fig. 2) increases by a factor of about 4.5 compared to the threshold with the modulator open circuited, indicating a substantial variation in intracavity loss.

The devices were modulated by application of both a dc

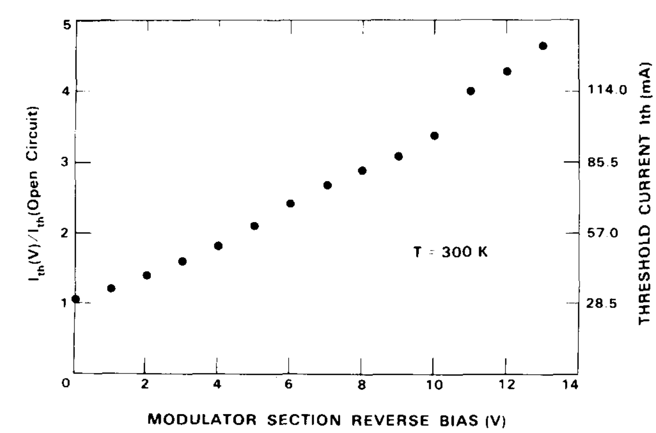

FIG. 2. Pulsed threshold, normalized to the threshold of the laser with the modulator open, as a function of modulator reverse bias.

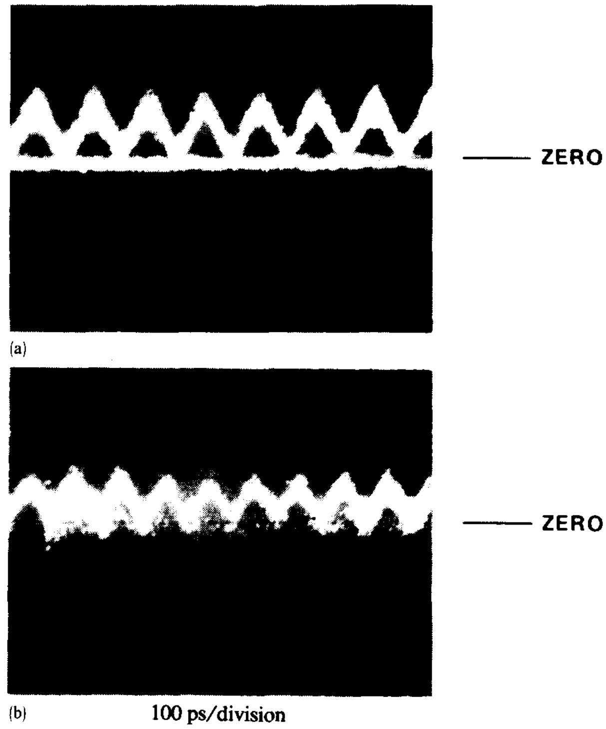

FIG. 3. (a) Continuous Q switching at 8 GHz; (b) Q switching at 10.2 GHz. Both figures have an extra trace to show the reference level with the light blocked. The intensity of the reference was reduced in (b).

voltage and a microwave signal to the modulator.[5] Typically 70–200 mW of microwave power and a few volts of dc reverse bias were sufficient to drive the unmatched modulator. The devices were modulated at rates between 2 and 10.5 GHz. The optical pulses out of the laser were collected and focused on a back-illuminated 25-μm-diam GaInAs/InP *pin* photodiode with less than 70-ps full width at half-maximum response time.[10] The detector output was displayed on a sampling oscilloscope with a 20-ps rise time. Continuous Q-switched operation at a rate of 8 GHz with full on/off modulation is illustrated in Fig. 3(a). The laser amplifier was driven at 2.1 times the threshold of the device with the modulator open. The modulator was dc biased with 1.3-V reverse bias. 100 mW of microwave power was applied to the system. The actual modulator drive power was somewhat less due to insertion losses in the bias tee, cables, and connectors. Full on/off modulation was seen at 10.2 GHz as shown in Fig. 3(b), although the detected signal is smaller. In addition, modulation up to 10.5 GHz was observed although the signal is smaller still.

Various types of behavior including subharmonic operation and irregular pulsations can be seen when the operating conditions of the laser are varied. The effect of increases in the amplifier current at a fixed modulation frequency of 2 GHz is shown in Fig. 4. When the amplifier current was just sufficient to produce laser oscillation, laser pulses were observed at the modulation frequency as shown in Fig. 4(a). With increasing current, the intensity of the pulses increased, Fig. 4(b), until a transition region in which the laser pulses irregularly was encountered, Fig. 4(c). With still higher current, the laser again operated at the fundamental of the modulation frequency [Fig. 4(d)].

The qualitative behavior of the device can be under-

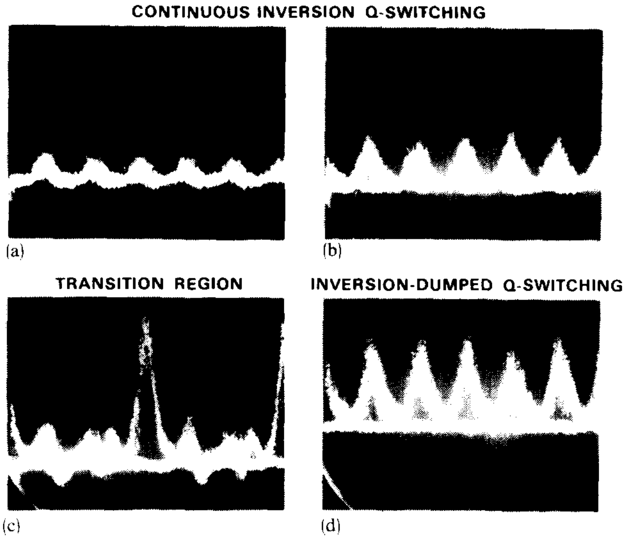

FIG. 4. Effect of increasing the amplifier current (a) 50 mA, (b) 54 mA, (c) 59 mA, and (d) 68 mA at 2 GHz with the modulator drive held constant. The dc threshold of this laser is 30 mA with the modulator open. (b)–(d) have an extra trace which shows the zero reference obtained when the light is blocked.

stood from previous modeling (cf. Fig. 7, Ref. 5). Just above threshold in Fig. 4(a), the electrons do not have sufficient time to recombine radiatively and most of the population remains in the inverted state. The device operates in a continuous-inversion mode of Q switching[5] in which the population inversion remains continuously high. In this mode, each time the modulator loss is lowered, a pulse is emitted without the time delay associated with rebuilding the electron population. In Fig. 4(b) the intensity of the pulses increases with the amplifier current because the gain increases. The modeling also suggests that as the current increases still further, the laser moves into a transition region in which the population intermittently reaches a level sufficient to dump below its low-loss threshold value (the population at threshold when the modulator loss is low) and does not recover to produce pulses at the modulation frequency as in Fig. 4(c). Finally, when the level of pumping increases sufficiently, the population recovers regularly and pulses are produced at the modulation frequency as shown in Fig. 4(d). In this mode of operation the population regularly dumps below threshold. The height of the pulses in Figs. 4(a) and 4(b) compared to Figs. 4(c) and 4(d) is consistent with inversion-dumped Q-switched operation since large pulses are expected when the population rapidly drops below its low-loss threshold. The present results provide the first experimental evidence of a continuous-inversion Q-switching mechanism.

The results reported here demonstrate Q-switched diode lasers with low threshold current. The lasers have been modulated at rates of 10 GHz and should be useful for optical fiber communication systems and other applications requiring such high rates.

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