Journal of Engineering, National Chung Hsing University, Vol. 13, No. 2, pp. 91-96 (2002)

850-nm VERTICAL-CAVITY SURFACE- EMITTING LASERS WITH A WAFER-BONDED METAL-MIRROR SI SUBSTRATE

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Key Words: vertical-cavity surface-emitting laser (VCSEL), mirror substrate, wafer bonding, distributed bragg reflector.

ABSTRACT

An 850-nm vertical-cavity surface-emitting laser (VCSEL) with a Au/AuBe/TaN/Ta/Si mirror substrate has been demonstrated by low-temperature wafer bonding. It is found that the mirror substrate can be used as the bottom reflector to enhance the reflectivity of bottom distributed Bragg reflector. The metal mirror also served as the adhesive layer and ohmic contact layers to bond the Si substrate and the VCSEL epilayers. As the mirror-substrate bonded VCSELs excited by continuous-wave current at room temperature, they present lower threshold current density and differential resistance (22 A/cm^2, 35 Ω) as compared with those of the original VCSELs on GaAs substrates (77 A/cm^2, 60 Ω). This feature is attributed to the Si substrate provides a good heat sink.

具晶片接合金屬鏡面矽基板之 850-nm 垂直共振腔面射型雷射

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關鍵詞：垂直共振腔面射型雷射(VCSEL)，鏡面基板，晶片接合技術，分佈式布拉格反射鏡。

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摘　要

具 Au/AuBe/TaN/Ta/Si 鏡面基板之 850 nm 垂直共振腔面射型雷射(VCSEL)已被用低溫之晶片接合技術製作成功。由研究發現鏡面基板能被用來當作下反射鏡，加強下分佈式布拉格反射鏡之反射率，此一金屬反射鏡面亦當作黏貼層與歐姆接觸層之作用，用以接合矽基板與 VCSEL 之磊晶膜。當鏡面基板接合之 VCSEL 於室溫被連續波之電流注入時，此類 VCSEL 之臨界電流密度與差動電阻(22 A/cm^2, 35 Ω)較黏貼前長晶於砷化鎵基板之 VCSEL (77 A/cm^2, 60 Ω)低。

1. INTRODUCTION

It is well known that the optimum device performance may not be realized in a single material, but in a variety of disparate materials for a given application. Heteroepitaxy offers an effective integration method. However, it has remained a challenge due to lattice constant mismatch between semiconductor systems. The heteroepitaxial growth of mismatched materials can result in highly defective layers, which degrades or inhibits device operation. An alternative to lattice-mismatched growth is the wafer bonding of an epitaxial thin-film substrate from a growth substrate (growth under lattice-matched conditions) to a host substrate of a different material. Wafer bonding allows materials with different lattice constants to be bonded together without generating a substantial number of defects in regions that are critical to device operation. A wide variety of wafer bonding techniques have been reported in the literature. The most common bonding techniques are fusion bonding, anodic bonding, and eutectic bonding [1-3]. It is worthy to note that robust bonding achieved at low temperatures is desirable. It can minimize unwanted dopant diffusion and materials stress that results from different thermal expansion coefficient. In our previous study, we have demonstrated that the performance of light-emitting diodes (LEDs) can be improved by bonding the AlGaInP-LED to a metal mirror at a low temperature (≤ 350 $^{\circ}$C) and a short thermal duration (≤ 30 min) [4-6]. The reflective metal substrate (MS) can directly be fused onto the device structure before selective removal of the GaAs substrate. It was found that the metal mirror almost has the same reflectivity as a multi-layer distributed Bragg reflector (DBR), especially for the long wavelength ($\lambda > 850$ nm). Furthermore, the Si substrate (thermal conductivity: 1.5 W/cm-K) has 3.26 times higher thermal conductivity than GaAs (0.46 W/cm-K), and thus providing a good heat sink. The small series resistance and good heat sink substrate are two important factors to eliminate the joule heating effect and thus increasing the quantum efficiency of the bonded LEDs.

On the other hand, 850-nm vertical-cavity surface-emitting lasers (VCSELs) are practically useful for optical interconnects because of the compatibility with Si- or GaAs-based receivers [7]. If the VCSEL can be fabricated on Si substrates directly, it offers the possibilities of integrating lasers with microelectronic circuits. Moreover, for the VCSEL application, the heat conductivity of substrate is an important issue, because the host substrates with higher thermal conductivity can also reduce the thermal impedance of VCSELs [8]. In this paper, we present 850-nm broad-area VCSELs fabricated on Si substrate employing the low-temperature MS-bonding technique. It provides the solid-phase reaction between the MS and the semiconductor at low temperature and forms of non-spiking ohmic contacts to both VCSEL-epilayers and Si substrate. It is fairly easy to get a mirror-smooth surface on the wafer-bonded sample after the removal of the GaAs substrate. The metals serve not only as the adhesive layers to bond the Si substrate and VCSEL epilayers, but also as a reflector mirror and ohmic contacts layers. Details of the device performance of the 850-nm VECSEL bonded to Si substrate will be discussed.

2. EXPERIMENTS

In order to make sure the function of mirror substrate, a conventional 850-nm VCSEL structure was employed in this bonding work (i.e. bottom n-type DBR pairs ≥ p-type top DBR pairs). The VCSEL structure was grown on (100) n^+-GaAs substrate using low-pressure metal-organic chemical vapor deposition at 730°C. The structure contains a 200 nm AlAs etching stop layers, thirty pairs n-type bottom DBR, GaAs/AlGaAs quantum wells in the active region, and twenty pairs p-type top DBR. The DBR is consisting of $Al_{0.16}Ga_{0.84}As$-$Al_{0.92}Ga_{0.08}As$ with parabolic heterointerface grading. The wafer bonding was initiated by depositing both the VCSEL wafer and the TaN/Ta/Si wafer with metallic adhesive layers of AuBe/Au. The Ta/TaN films on the host Si substrate was used to improve the adhesion between the AuBe/Au and Si substrate. The VCSEL and Si wafers were placed together so that the metal surfaces were in contact, as shown in Fig. 1. It is worthy to mention that the surface preparation does not start with etching one or two-dimension array of channels in one or both of the substrates to be bonded. The etching process is necessary for direct bonding due to the high temperature (>600°C) process [9]. Because the MS-bonding temperature is relatively lower (350°C), the interdiffusion between the epilayers can be minimized during the bonding process. Thus, the whole epilayer can be processed for the VCSEL applications. The wafer pair was held together into a graphite-bonding tool and heated to 350°C for 30 min in a N_2 ambient. After the bonding process, the GaAs substrate was selectively removed by chemical etching. The photograph of the completed grafted wafer is shown in Fig. 2. Films size as large as 2 cm on a side have been bonding with mirror-like surface quality, and it is expected that even larger area may be transferred in this way.

To facilitate rapid characterization of the MS-VCSEL, the broad-area VCSEL devices were made. First, the epilayers of VCSEL were etched by inductively coupled plasma to form mesas with sizes 150 μm × 300 μm. The p-contact is directly laid on the metal mirror. Then the top surface is coated with SiO_2 layer by plasma-enhanced chemical vapor deposition. A second mesa is then etched to the n-GaAs contact layer (15 μm/25 μm) using the same etching procedure. Finally the AuGeNi contacts were deposited on the mesa tops, which were subsequently alloyed at 420°C for ohmic contacts. As shown in Fig. 1(d), both of the contacts are placed on the top side of the structure to bypass the Si substrate. The bonded-VCSEL structure was examined using scanning electron microscopy (SEM, JEOL 6400). A Bio-Rad rapid photoluminescence mapper (RPM 2000) was used to measure the reflectivity of DBR. The semiconductor parameter analyzer (HP 4155B) was used to monitor the current-voltage characteristics of the VCSELs.

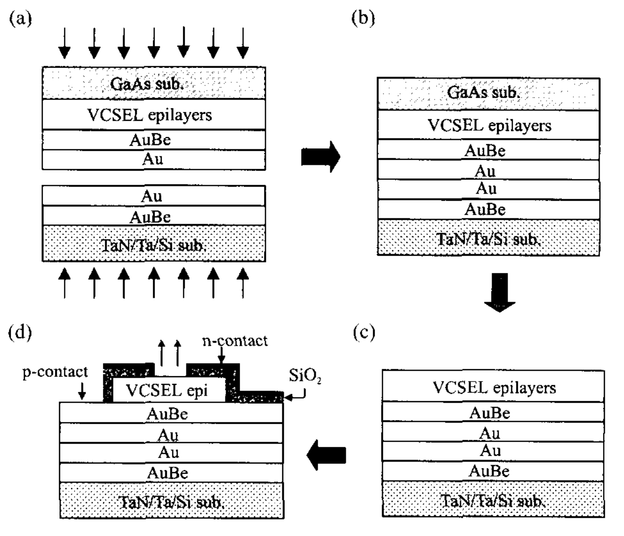


Fig. 1 Low-temperature bonding process of 850-nm VCSEL wafer and Si substrate with metal mirror

3. RESULTS AND DISCUSSION

It has been reported that the GaAs/AlAs is easily to disorder at high temperature: disorder coefficients of 1.14×10^{-25} cm^2/s. It leads to an interface roughening after high-temperature fusion bonding. This phenomenon cannot occur in this work due to the low temperature bonding process. Fig. 3 shows the scanning electron micrograph of a bonded MS-VCSEL. It was found that the bonding interface of AuBe/Au/Au/AuBe has been fused. The interface between the metals cannot be distinguished. Furthermore, there is no roughening of the epilayer surfaces introduced by the bonding process. The sharpness of the DBR interfaces indicates that there is no interdiffusion or disordering between the $Al_{0.16}Ga_{0.84}As$-$Al_{0.92}Ga_{0.08}As$ pairs. These suggest that the mechanism of the MS bonding was *via* solid-phase reaction, resulting in a non-spiking ohmic contact between VECSEL epilayers and the Si substrate. The low-temperature bonding process can avoid the potential damage to the VCSEL structure arisen from high-temperature fusion bonding.

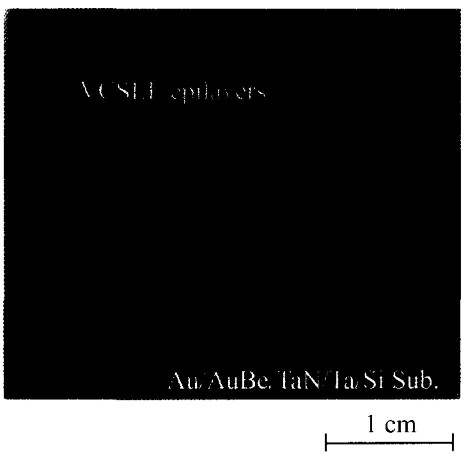


Fig. 2 Top-view photograph of a successfully wafer-bonded 850-nm VCSEL epilayer on Si substrate with metal mirror

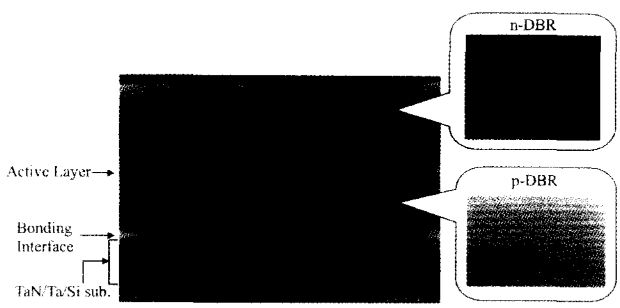
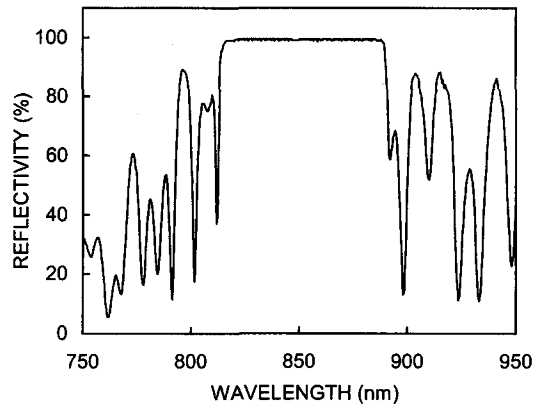


Fig. 3 Cross-sectional SEM micrograph of a bonded MS-VCSEL

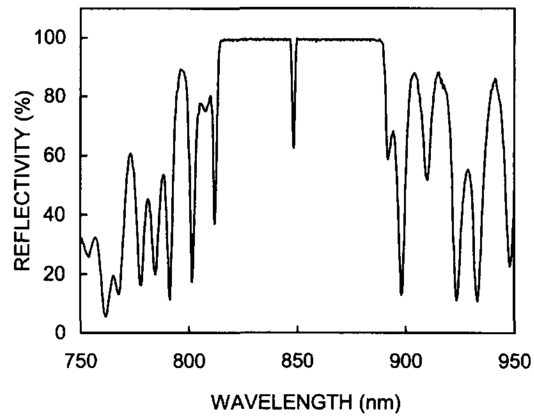
Another evidence of the quality of the fused interface can be examined by optical reflectivity. Figure 4(a) shows the measured reflection spectrum of the MS-bonding VCSEL. The reflectance of VCSEL is measured using a gold mirror as reference. Obviously, the reflectivity was still maintained up to 99.95% at 820 to 890 nm. Measurements on the bonded MS-VCSEL show that the mirror reflectivity is actually as high as theoretically expected one. This suggests that the bonding parameters (low bonding temperature and short duration time) do not destroy the optical quality of DBRs. Note that the order of the top (p-DBR) and bottom mirrors (n-DBR) has been reversed after bonding in this work. The calculated reflectivity of the original n-DBR is 99.95%. It is consistent with the measured data. Due to the high reflectivity, the dip resulted from the Fabry-Parot resonator does not be measured. From these results described above, the MS-bonding can alleviate automatically these problems caused by the high-temperature direct bonding, while preserving the high-performance optical properties. Figure 4(b) shows the reflectivity of the original top mirrors before bonding. The measured reflectivity is about 99.4%. The figure clearly shows the dip at about 850 nm resulted from the Fabry-Perot resonator. Since the original top p-DBR is bonded to mirror substrate, it becomes the bottom mirror of the MS-VCSEL. The bottom mirror becomes the twenty pairs p-DBR in conjunction with the AuBe/Au reflecting metal. Whether the combined mirror could improve the reflectivity of the bottom p-DBR of the MS-VCSEL, it will be further studied from the performance of MS-VCSEL.

The performance of the VCSEL devices is measured on a copper stage at room temperature without additional heat sink. Figures 5(a) and (b) shows the light output versus current versus voltage (*L-I-V*) curves of the original and MS-bonded VCSEL, respectively. It was found that the MS-bonded VCSEL has lower threshold current (10 mA) than the original VCSEL does (35 mA). The corresponding current density is 22 A/cm^2 and 77 A/cm^2 for the MS-bonded and original VCSELs, respectively. This suggests that the wall-plug efficiency of the VCSEL will be improved after this wafer-bonding process. The differential resistance of the MS-VCSEL (35 Ω) is lower than that of the original VCSEL (60 Ω). It can be explained by the present MS-VCSEL structure, where the current does not flow through the Si substrate (contact pattern shown in Fig. 2). Furthermore, the output power of MS-VCSEL is found to increase with increasing the injection current. It dose not present saturation as current up to 200 mA, while the *L-I* curve of the original VCSEL saturates as the current increases to 80 mA. On the other hand, the power efficiency of the present MS-bonded VCSEL is limited by the inversion of the order of top and bottom mirrors due to the conventional VCSEL structure used, where the output coupled to n-DBR has high reflectivity than that of the bottom p-DBR. Nevertheless, the bottom metal-mirror substrate can enhance the reflectivity of p-DBR in the MS-VCSEL. It makes more output power emit through the n-DBR. From the measured data of Fig. 5(b), it suggests that the combined bottom mirror indeed can enhance the reflectivity of the bottom p-DBR. Further demonstrating the metal mirror instead of the DBR for the MS-VCSEL requires redesign the VCSEL structure and the study is on the way.

On the other hand, from the VCSEL spectra shown in the insets of Fig. 5, it was found that the wavelength of emission and the full width at half-maximum presents slight red-shift and narrower, respectively, for the MS-VCSEL as compared those with the original VCSEL. These might be due to the fact that the GaAs substrate was removed and the stress of MS-VCSEL epilayers was relieved. Moreover, for the traditional p-up VCSEL structure, the heat generated at the p-DBR must be dissipated through the active region and n-DBR before reaching the substrate. Since the heat conductivity of DBR in the vertical direction is always low, the subsequent rapid increase in temperature at the active region is inevitable. In the present MS-bonded VCSEL structure, the p-DBR directly contacts with the substrate through the metal and the heat generated at the p-DBR can be conducted to the Si substrate more efficiently. From the *L-I-V* curves shown in Fig. 5, it can be observed that the power of MS-VCSEL does not present saturation as the injection current increase to 200 mA. This feature is attributed to the Si substrate providing a good heat sink.



(a)



(b)

Fig. 4 Reflection spectra of the top mirrors of (a) MS-bonding VCSEL and (b) original VCSEL before bonding

4. CONCLUSION

850-nm MS-VCSELs on Si substrates have been fabricated by the wafer bonding technique at low temperatures and short bonding duration. The metal-mirror acts not only as an adhesive layer, but only be as an ohmic layer and reflective mirror. The metal-mirror can improve the reflectivity of the bottom p-DBR. The MS-bonded VCSEL has lower threshold current and differential resistance than the original VCSEL does. The output optical power of the MS-VCSEL does not present saturation as the injection current increase to 200 mA, while the *L-I* curve of the original VCSEL saturates as the current increases to 80 mA. Obviously, the mirror-structure Si substrate provides good heat dissipation.

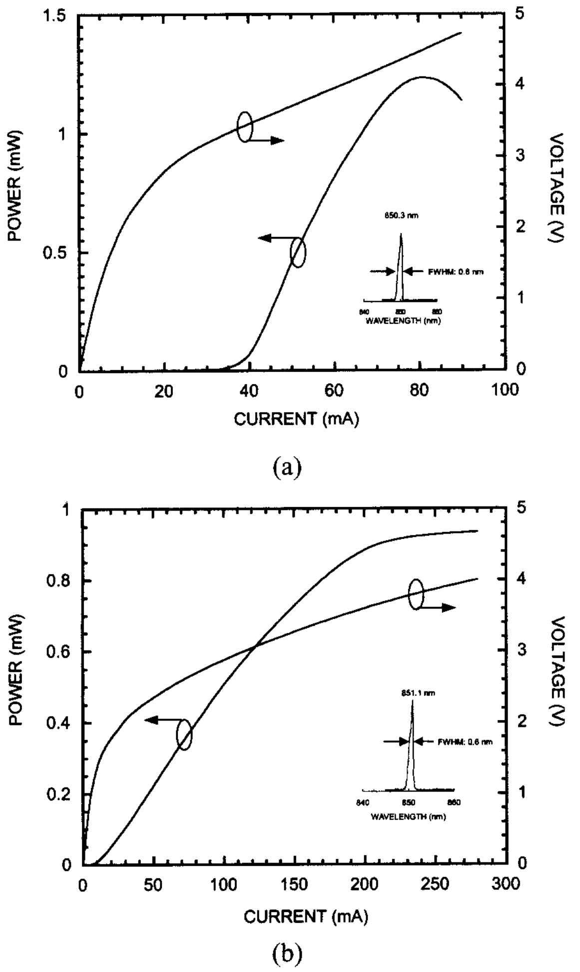


Fig. 5 L-I-V curves of the (a) original and (b) bonded MS VCSELs. The insets show the typical emission spectra of the original and bonded-MS VCSELs

5. ACKNOWLEDGMENTS

This work was supported by the National Science Council of Republic of China under contract No. NSC 89-2215-E-005-010.

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Manuscript Received: Mar. 6, 2002
Revision Received: Mar. 26, 2002
and Accepted: Apr. 2, 2002