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Thermal compression wafer bonding of tungsten applied to fabrication of small-period tungsten woodpile structures

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ABSTRACT

In this paper, we report on the thermal compression bonding of tungsten at very high temperatures and pressures, and the realization of a 3D tungsten woodpile structure using this method. The structure is fabricated by holographic patterning followed by dry etching of tungsten-on-Si (for the base) and tungsten-on-oxide-on-Si (for subsequent layers). The patterned layers are then wafer-bonded together at a pressure of about 50 MPa and a temperature about 700 °C for several hours. The substrate with the oxide-on-Si is then removed by a combination of lapping (for the bulk of the Si substrate), selective dry etching of Si with SF_6 (for the remaining few microns of Si), and buffered oxide etch for selective removal of the oxide, leaving the two layers of tungsten firmly bonded. The process is repeated for additional layers. Bonding strength for the tungsten layers is between 2 and 9 MPa, depending on bonding conditions. This is a potential pathway for manufacturable fabrication of three-dimensional small-period (~500 nm) tungsten woodpile structures, which may have particular applications for high-efficacy incandescent filaments.

1. Introduction

New techniques in bonding or processing innovations act as tools and important enablers for device development. In particular, wafer bonding has been the key to a vast array of technologies [1,2] including fabrication of Si-on-insulator wafers [3], devices based on bonding techniques [4] and heterogeneous integration of otherwise incompatible materials systems [5]. While thermal compression bonding is used for Au [6], wafer bonding between other metals is less common. In this paper, we report, to our knowledge for the first time, a process suitable for thermal compression bonding of tungsten-to-tungsten. As a metal with the highest melting point, W is quite challenging to bond, and extremes of temperature and pressure are needed.

Development of this process is driven by our research work for fabricating 3-D tungsten photonic crystals for the purpose of using them as selective thermal emitters. Fabrication of 3D tungsten photon crystals in general is a difficult process. Our approach is to design two dimensional (2-D) phototonic structures having the periodicity suitably chosen to suppress thermal radiation in the infrared region of the electromagnetic spectrum and then to bond these 2D-structures to form a 3D-woodpile structure. Other approaches are described in the literature including self-assembly, for opal structures, and layer-by-layer deposition, patterning, and planarization followed by deposition of the next layer for woodpile structures.

In this paper, we demonstrate a new technique for the fabrication of an optical-scale tungsten photonic crystal bandgap structure with a combination of holographic patterning and wafer bonding. First, we estimate the proper configuration for such a structure using finite difference time domain (FDTD) design simulation tools from Lumerical for suppressing thermal emission just above the visible (>700 nm) needed for a high-efficacy incandescent light source. We then fabricate the first layers of a woodpile tungsten photonic crystal using a novel holographic patterning and wafer bonding scheme to build the structure up layer-by-layer. To our knowledge, this is the first reported bonding of tungsten by thermal compression, and the first demonstration of fabrication of an "optical-scale" tungsten photonic crystal.

2. Simulation

While the focus of this paper is on the bonding process and not the device results, we would like to briefly describe the motivation for an optical-scale tungsten photonic band gap, and the design process to achieve it.

Our primary objective is to form a tungsten filament patterned into a "woodpile" type photonic crystal (PhC) [7–10] which suppresses emission above a cutoff wavelength in the infrared. This structure is required to possess an omnidirectional photonic band gap, having the high energy cutoff at a certain wavelength depending on structure

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dimension such that it does not allow transmission of any light in any direction at wavelengths longer than cutoff wavelength. For such a material used as a thermal emitter, the luminous efficacy should be significantly higher than that of a conventional incandescent light source, since emission of radiation in the spectral region at wavelengths longer than the cutoff wavelength will be suppressed. In this context, it is worthwhile to note that only ~13 % of the radiation from a tungsten filament lamp at 3000 K is deposited into the visible region.

The ideal photonic woodpile has two orthogonal grid layers, as pictured in Fig. 1. The third layer is then parallel to the first but offset horizontally by half the rod-to-rod spacing, as shown. The fourth layer is parallel to the second, also offset by half the rod-to-rod spacing. The entire structure is then repeated to build the 3D-woodpile structure.

A typical structure and associated bandstructure calculation was done using a FDTD method with commercial software (Lumerical). The rod height is 80 nm, the width is 50 nm, and rod-to-rod spacing is 500 nm. The structure suppressed emission above about 0.7 µm in all dimensions. When fabricated, this device may offer enhanced emission outside of the band gap compared to an ordinary W thermal emitter [11]. This has the theoretical potential for achieving the efficacy of a fluorescent bulb while maintaining the perfect color rendering index of an incandescent light source. Similar structures are also being explored for application as thermovoltaic sources [7]. Further details and some preliminary experimental results are reported in [12].

We note that with this method, while varying layers can be placed orthogonal to one another, they cannot be aligned within a half-period as they should be for a perfect woodpile photonic crystal. Previous simulations have suggested that this will not fundamentally change the photonic bandgap of the crystal [13]. Thus, the tradeoff for this attractive parallel aufbau process is the loss of the ability to place the grating precisely within the period of the crystal.

3. Fabrication process

Several methods are used to address the challenges of fabricating 3-D photonic crystals, including self-assembly [7] as well as layer-by-layer stacking with electron beam lithography, deposition, etch and planarization techniques[4]. All of these techniques include tradeoffs between fabrication time, photonic atom placement, and ease of manufacturability. Many of them rely on e-beam lithography, which is inherently not a cost-effective process suitable for large scale manufacturing.

The technique used here includes wafer-scale holographic patterning followed by wafer bonding, which are inherently parallel, bulk processes and thus can be more easily adapted for large scale manufacturing compared to many other alternatives. Fig. 1 shows the schematic of the whole process flow. First, submicron period gratings are patterned on tungsten on Si or SOI wafers using holographic lithography, followed by dry etching. Two patterned tungsten layers are then assembled with thermal compression wafer bonding. The extra wafer substrate is removed by lapping, and selective wet and dry etching processes. This process will enable fabrication of wafer-scale, three-dimensional photonic crystals with tungsten grating period of ~500 nm.

The bonding and removal processes have to be repeated several times until the desired number of tungsten layers is reached. Each of these processes are wafer level processes which should enable parallel fabrication of large areas of tungsten woodpile structures.

3.1. Holographic lithography and reactive ion etching

Holographic lithography [14] is used to pattern tungsten grating on silicon and silicon dioxide wafers. First, SU-8 2000.2 (nominally 200 nm thick negative resist) is spun on 100 nm thick tungsten film deposited on silicon and silicon dioxide-on-silicon substrates respectively with spread speed of 500 rpm for 5 s and spin speed of 4000 rpm for 30 s followed by pre-exposure bake at 65 °C for 1 min and 95 °C for 2 min. The samples are exposed using a holographic lithography setup with exposure time of 5 min and a target period of 500 nm. After that, they are post-exposure baked at 95 °C for 1 min before developed with SU-8 Developer and rinsed by IPA. Then the samples are loaded into RIE chamber and etched using 5 sccm CF_4, RF power of 65 W, 30 kHz frequency and a total etching time of 1 min 15 s.

3.2. Bonding process

Unlike 1-D and 2-D PhCs, 3-D PhCs require the periodic arrangement of materials with different dielectric constant in all three dimensions. With available microfabrication techniques, it is relatively straightforward to realize the periodic structure (gratings) in the *x*–*y* plane; the major challenge is to repeat the same periodic structure in *z* direction, even with the simplest case of 3-D PhCs-woodpile structure. To stack the periodic structure layer by layer, a thermal compression bonding-technique for tungsten is developed and adopted. Previous work [6,15,16] has demonstrated successful

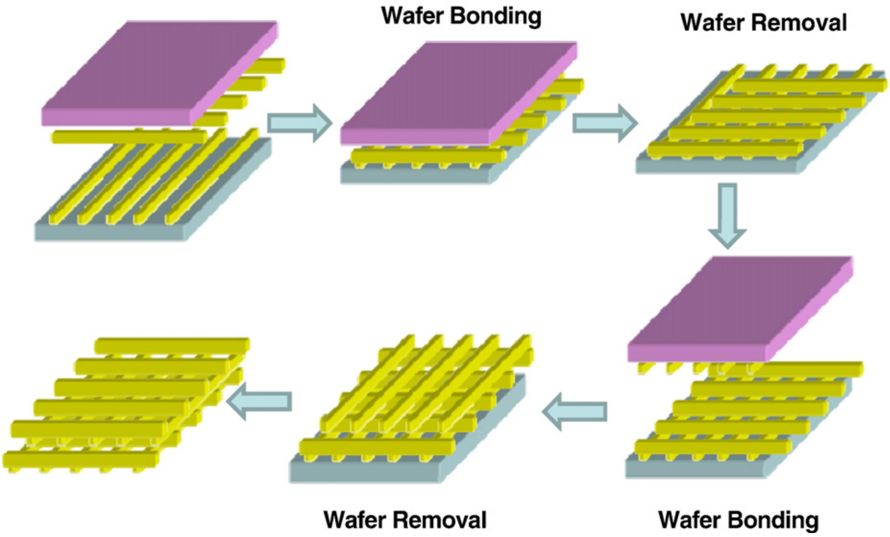

Fig. 1. Fabrication technology for W multiple array grids. Patterning followed by wafer bonding and topside wafer removal, repeated to construct the structure.

wafer-level thermal compression bonds using Au. This is, to our knowledge, the first demonstration with tungsten. It is the most critical step in building a 3D-wood pile structure from 2d-structures.

To realize bonding, first the patterned tungsten layers to be bonded are cleaned in an oxygen plasma using 20 sccm oxygen at 200 W for 5 min. Then, patterned tungsten layers on a silicon wafer substrate and a silicon dioxide-on-silicon wafer substrate are placed together with the tungsten wires oriented orthogonally and in intimate contact. They are mounted between two graphite pieces and loaded in a bonding clamp apparatus consisting of two stainless steel plates with four bolt holes drilled around the perimeter (Fig. 2). The two stainless steel plates are tightened together through a torque applied to the bolts at a fixed value around 35 in.-lb.

To optimize the process and bonding parameters, including bonding pressure uniformity, the measured pressure between two bonded pieces is visualized by Fuji prescale pressure measuring film. The film is placed between two layers of Si and the fixture torqued to a particular value with the color of the film indicates the pressure experienced. Our initial bonding pressure is around 50 MPa.

The apparatus with bonding pieces inside is placed in a furnace in a nitrogen atmosphere. The furnace was gradually warmed up (50° every 30 min) to ~700 °C, held there for 1–6 h, and then stepped down. During the heating process inside the furnace, the actual pressure applied on the samples is increased due to the thermal expansion of the fixture. After being cooled to room temperature, the pieces were removed.

4. Results and discussion

The bonding stress at failure for different pieces was measured through destructive tensile testing with an Instron 4206 tensile testing machine. Fig. 3 shows the failure stress vs. bonding time at 700 °C for these samples. The bonding strength increased monotonically with bonding time, and ranged from 2 to 9 MPa.

After successfully bonding patterned tungsten, one substrate needs to be removed to uncover the stacked W wires in between and expose them for further bonding. Here we combine mechanical removal of the material by lapping, with selective dry and wet etching, to expose clean tungsten surfaces for continued bonding. A Logitech PM5 Lapping machine is first used to remove the major thickness of silicon dioxide substrate. The thickness of the oxidized silicon wafer (a silicon wafer with a layer of ~1 μm silicon dioxide) is about 360 μm. About 350 μm of Si is removed with the lapping machine using 9 μm alumina abrasive and lapping speed of 25 rpm. The average removal speed is ~12 μm/min. To avoid overlapping the sample, the rest of the silicon is etched away with reactive ion etching that etches Si preferentially over silicon dioxide. Etch conditions are a flow rate of SF$_6$ of 20 sccm, RF power of 200 W, and frequency of 30 kHz. The etch rate of silicon under this condition is ~0.3 μm/min. Since the etching rate of silicon dioxide is much less than that of silicon, the oxide layer works well as a mask layer to keep tungsten from being etched away by SF$_6$. After removal of the residual silicon with reactive ion etching, buffered oxide etch is used to remove the exposed silicon dioxide and uncover the tungsten woodpile layer on the silicon substrate. The whole process can be repeated several times to stack multiple layers of tungsten logs. Fig. 4 shows the SEM images of tungsten grating on silicon after two bondings with three layers of woodpile structure.

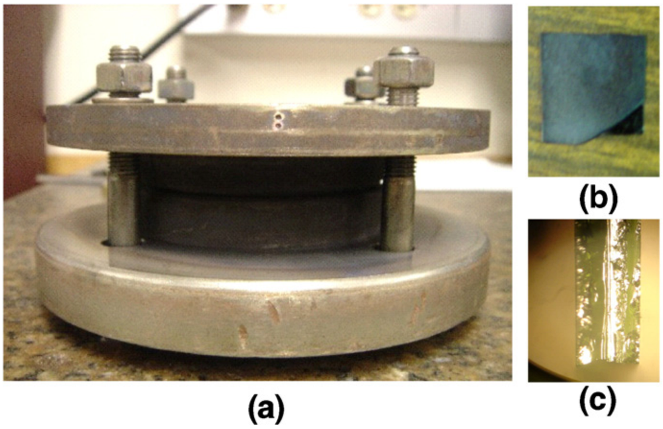

Fig. 2. (a) Wafer bonding chuck, showing two pieces of graphite sandwiched between two pieces of W clamped by bolts; bonded W on Si, showing (b) top view, and (c) side view.

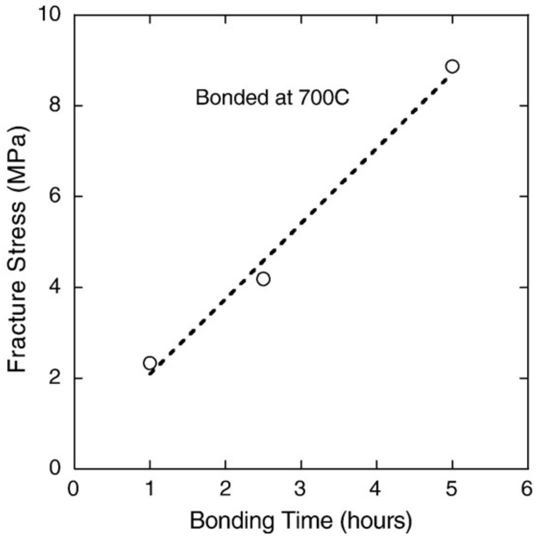

Fig. 3. Failure stress vs. bonding time at high temperature.

Three layers of bonding have been realized up to cm^2 area. Current efforts are focused on refining the bonding process (particularly the clamp apparatus) to make the pressure more uniform and allow reliable uniform bonding over larger areas.

5. Conclusions

In this paper, a technique is demonstrated for wafer bonding repeated layers of tungsten for fabricating tungsten photonic crystal woodpile structures. Bonds realized had failure strengths up to 9 MPa, which is a high value for this sort of bond. This technique may be applied to realize optical-scale tungsten woodpile structures on a wafer scale without the need for further patterning for potentially highly efficacious black-body emitters. Three layers of a woodpile

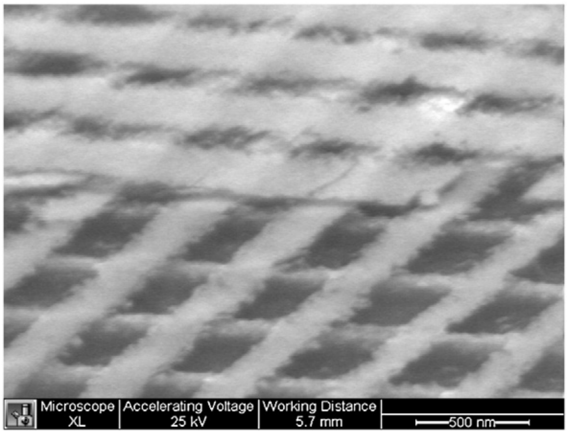

Fig. 4. SEM picture of "woodpile" structured tungsten.

structure are fabricated with the appropriate dimensions for efficient black-body emission. Further work is ongoing in increasing the number of layers and achieving more uniform bonding, and in characterizing the black-body emission of this structure.

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