

Tiny Tapeout: A Shared Silicon Tapeout Platform Accessible To Everyone

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Index Terms—ASIC, Multi Project Chip, Open Source Silicon, Tiny Tapeout.

I. INTRODUCTION

TINY TAPEOUT is a multi project chip platform that makes it easier and cheaper to get application specific integrated circuit (ASIC) designs manufactured.

Open source tools and process design kits (PDK [1]) are used so no licenses or non disclosure agreement (NDAs) are required. As the tools run on remote cloud servers no software needs to be installed locally on the user's machine. As long as the template structure is followed, however, Tiny Tapeout does support the use of proprietary tools.

Each Tiny Tapeout ASIC production run sees around 400 open source designs multiplexed to 24 general purpose input/output (GPIO) pins. After manufacture the resulting chip is mounted to a demonstration board for ease of testing. Each chip contains a copy of every design, which can be selected and tested in turn.

At the same time each participant submits documentation for their design, which used to create a printable datasheet [2] along with an online project index at TinyTapeout.com/runs/ [3]. The datasheet helps participants explore other designs on the chip in addition to their own.

By separating the cost of area on a silicon wafer and the finished physical chip, the Tiny Tapeout participant group is able to share the cost of chip packaging and circuit board manufacture while still being able to test and measure all the designs on the chip. For use in educational settings it is possible for multiple students to submit individual designs while sharing the finished chips and circuit boards, reducing the cost still further.

Each Tiny Tapeout tile (Fig. 1) is approximately $160 \times 100 \mu\text{m}^2$. This provides enough room for around 1,000 logic gates when built upon the SkyWater 130nm open source PDK. Multiple tiles can be interconnected to enable larger designs, while analog and mixed signal support is on the roadmap for the next shuttle.

Community engagement in Tiny Tapeout has been strong, with 756 designs submitted over the first five shuttles. A curated selection of projects is provided in section IX. An online chat server for participants has 1,000 members with 1,600 subscribers to the project's mailing list. Individuals submitting designs to Tiny Tapeout tend to self identify as hobbyists, students, and teachers, as shown in Fig. 2.

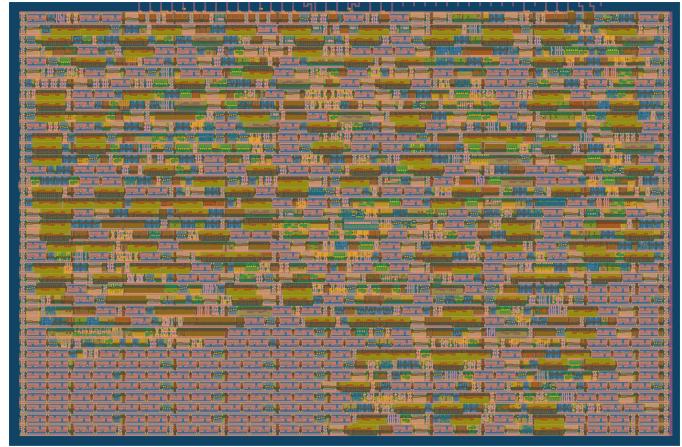


Fig. 1. A 2-D render of a single Tiny Tapeout tile.

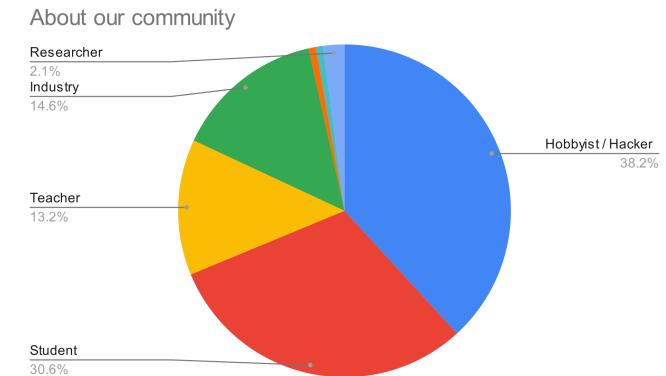


Fig. 2. Tiny Tapeout 04 participant self identification.

The first [4] Tiny Tapeout production run, which was provided as a free and experimental effort with a total of 152 designs, was submitted to the seventh Google-sponsored [5] lottery based multi project wafer (MPW) shuttle in September 2022. The next four shuttles combined a total of 582 designs, all sponsored by and manufactured through the Efabless [6] chipIgnite MPW service. Table I shows a summary of all Tiny Tapeout shuttle runs to date.

The rest of this paper will detail the Tiny Tapeout design flow, multiplexer evolution, circuit board design, the results of post production silicon testing, and the project's next steps.

TABLE I
TINY TAPEOUT SHUTTLE SUMMARY

| Run | Launched | Shuttle | Designs | Delivery date | Architecture | Number of IOs | IO bandwidth | Analog support |
|------|------------|---------|---------|---------------|---------------------------|---------------|--------------|----------------|
| TT01 | 2022-08-17 | MPW7 | 152 | n/a | Scan chain | 16 | 5 kHz | no |
| TT02 | 2022-11-09 | 2211Q | 165 | 2024-01-30 | Scan chain | 16 | 5 kHz | no |
| TT03 | 2023-03-01 | 2304C | 249 | 2024-02-28 | Scan chain inverted clock | 16 | 10 kHz | no |
| TT04 | 2023-07-01 | 2309 | 143 | 2024-04-15 | Mux | 26 | 50 MHz | no |
| TT05 | 2023-09-11 | 2311 | 174 | 2024-05-12 | Split Mux | 26 | 50 MHz | no |
| TT06 | 2024-02-01 | 2404 | TBD | 2024-11-30 | Split Mux | 38 | 50 MHz | yes |

II. DESIGN FLOW

Tiny Tapeout designs are primarily developed in the Verilog hardware description language (HDL) or Wokwi [7]. Wokwi is a web based visual schematic editor for hardware description, designed as an easier way for individuals with no prior HDL experience to get started. The Tiny Tapeout website [8] includes a basic Wokwi getting started guide, demonstrating how to use the tool to draw circuits, which is made available in English and Spanish.

The design flow has the participant create a GitHub [9] source code repository based on provided templates then add their ASIC design. This triggers automated tests and the generation of binary layout files in GDSII [10]. If all tests pass and the binary layout files are correctly generated, the design is then submitted to a quarterly shuttle for production in silicon.

The Tiny Tapeout GitHub templates [11] make use of GitHub Actions [12]—an automatic continuous integration system triggered every time the repository is updated. This reduces duplicated effort and makes it possible for Tiny Tapeout to support large numbers of participants without excessive technical overhead.

There are four main jobs in the continuous integration system:

- 1) GDS: installs OpenLane [13] and the SkyWater Sky130 [14] PDK, builds the binary layout files, and generates a summary of the design (Fig. 3). The summary includes utilization, standard cells used, a 2-D render (Fig. 1) and an interactive 3-D viewer (Fig. 4). This job can also optionally run a gate-level verification of the design.
 - 2) Verification: installs the YosysHQ open source computer-aided design (CAD) suite, which includes many common electronic design automation (EDA) tools; uses iVerilog [15] and cocotb [16] to run included testbenches.
 - 3) Documentation: generates a preview of the documentation.
 - 4) Precheck: runs design rule check (DRC) tests to ensure the design can be integrated into the multi project chip.

Successful GDS, Documentation, and Precheck job completion are all required for a design to be submitted to a shuttle for production. Verification is optional but highly encouraged. Submissions designed in Wokwi are able to make use of its integrated truth table testing system [17].

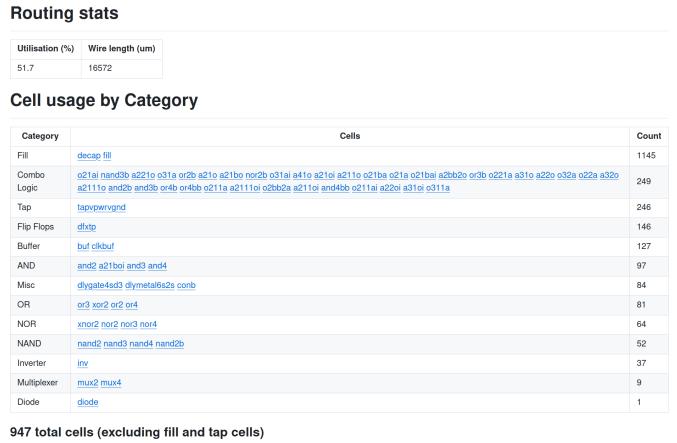


Fig. 3. A summary table from the GDS continuous integration job.



Fig. 4. The interactive 3-D viewer.

While the Tiny Tapeout continuous integration system can be run entirely in the user's web browser, it is also possible to install a local copy of the tools [18] on a participant's computer. Locally installed tools can help to reduce the time between design iterations, especially for the test and verification jobs.

III. SCAN CHAIN ARCHITECTURE

Tiny Tapeout started as an experiment in fitting as many designs as possible into the 10 mm² available on the Google lottery shuttles (Fig. 5). As a fast proof of concept, a scan chain was chosen. Each design had 8 inputs and 8 outputs. Clock and reset were optional and not treated specially. The chain was formed of scan flops [14], a type of flip flop with

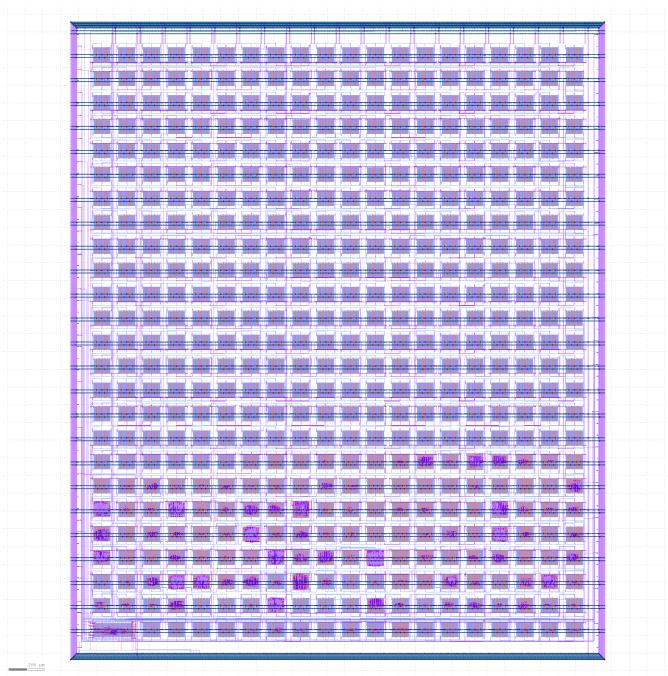


Fig. 5. 500 designs connected in a chain for TT01, with the scan chain driver in the lower left corner.

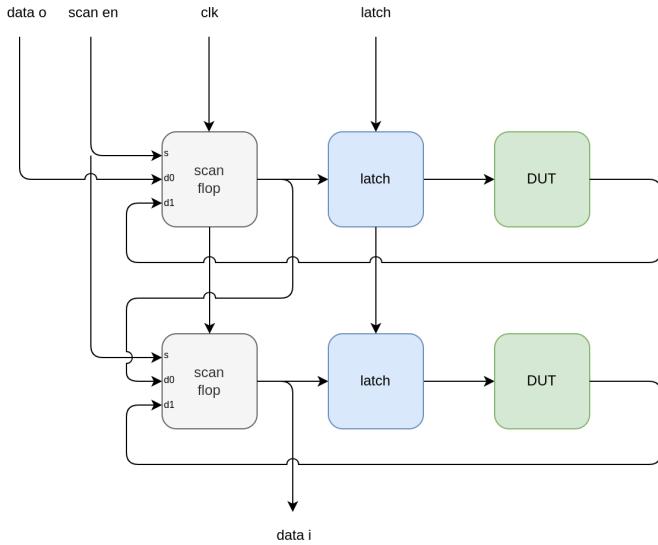


Fig. 6. A simplified view of 2 designs in the chain.

an integrated multiplexer at its input. An example showing a two-design scan chain is shown in Fig. 6.

Each design sends data into the scan flops secondary input and receives input from the output of the flop via a latch. The chain is built [19] by sending data from the output of the previous scan flop into the next scan flops's primary input.

This arrangement allows the loading of data into any of the designs, and then capturing the output and clocking that through the rest of the chain to the output.

While relatively easy to implement, the downside is the latency. The more designs in the chain, the longer it takes to send and receive data. For example, assuming a 50 MHz scan chain clock, 250 designs with 8 inputs and 8 outputs, the

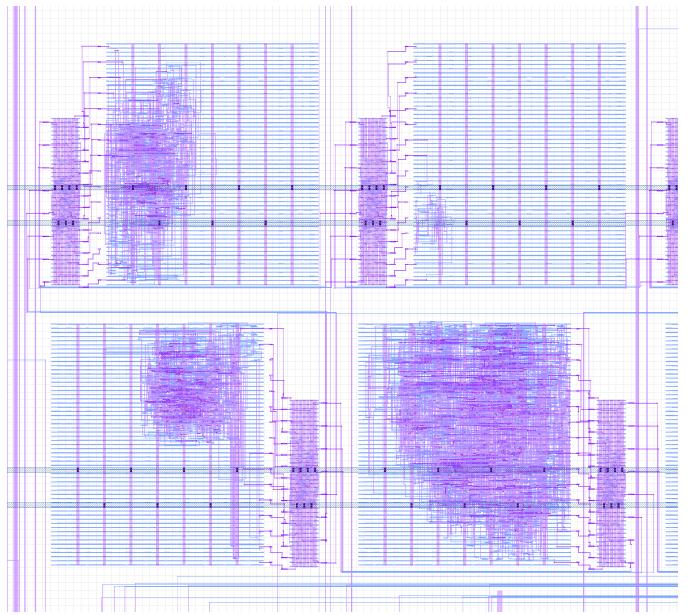


Fig. 7. TT02 designs with separate scan chain blocks.

maximum refresh rate is $50 \text{ MHz} / (8 \times 250) = 25 \text{ kHz}$.

TT01's scan chain was embedded into each design, which meant that a user could unintentionally remove it, breaking the chain. This risk was mitigated with a formal [20] equivalence check—proving the chain was present in the submitted design. For TT02 and TT03, the scan chain was separated into a separate macro block that the user can't modify.

Another concern was hold violations due to the large number of serially connected flops and potentially large clock skews due to long signal wires. This was mitigated by reclocking the output data with a negedge flop, providing substantially more hold margin.

After static timing analysis (STA) it was discovered that the clock duty cycle could change substantially due to the 500 sequential clock drivers. Depending on the clock buffers and capacitance between each design, the clock duty cycle could either increase or decrease, with this effect accumulated over the chain.

For TT01 and TT02 each design used two clock buffers, with the internal flops driven after the first buffer. TT03 used inverting clock buffers, with only one between the clock in and out. Fig. 8 shows a comparison between the TT02 and TT03 clock buffer designs. By inverting the clock between each design, any asymmetry in the clock pulse is evenly spread across the negative and positive cycles.

The verification effort [21] was broad and included a community review, register transfer level (RTL) and gate level (GL) simulation, Formal Verification [22], STA, layout vs schematic (LVS), DRC, and device level static verification [23].

IV. CIRCUIT BOARDS

After manufacture, the chips are mounted onto small carrier boards with 0.1 inch headers. This allows people with limited

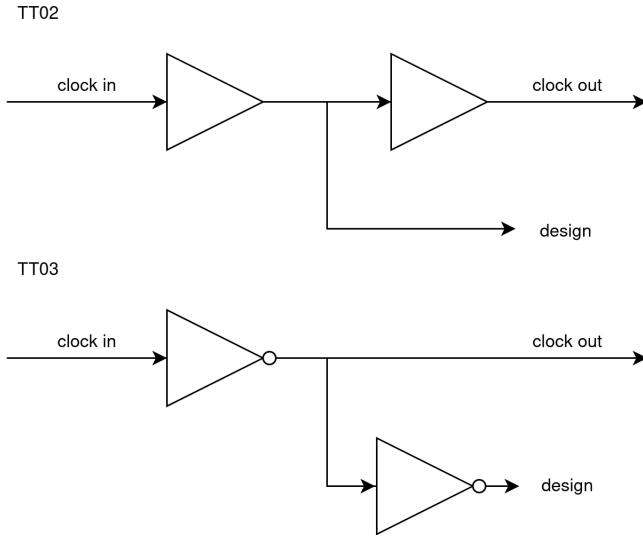


Fig. 8. TT03 buffers the output from the clock network into each design. Clock polarity is alternated between designs to minimize asymmetry between positive and negative cycles.

surface mount technology (SMT) assembly experience to build their own demonstration boards.

The carrier fits onto the demonstration board shown in Fig. 9. The demonstration boards are designed primarily for ease of use by beginners, with enough flexibility for power users. As all signals are below 50 MHz, no special layout was needed.

The demonstration board provides:

- USB-C for power connection,
- 1.8 V and 3.3 V power supplies for core and IO,
- 20 MHz oscillator,
- Buttons for reset and single-step clock,
- An 8-way DIP switch for inputs,
- A 9-way DIP switch for design selection,
- A 7-segment LED display for the outputs,
- Headers for all IO, including 2 standard Digilent ports (PMOD),
- A header to select the internal clock or provide one externally,
- A header to select internal or external scan chain driver,
- A header to engage an automatic clock divider in input pin 0.

V. SCAN CHAIN SILICON RESULTS

TT02 chips were received in October 2023, 11 months after the chips were submitted for manufacture on Efabless chipIgnite 2211Q. The chips were tested for the first time in public on a livestream [25]. The chain was validated, and a few of the designs were shown to be working.

In the following days another 30 designs were tested and shown to be working.

After measuring the clock asymmetry (Fig. 10) and maximum frequency it was decided to run the production boards with a 20 MHz oscillator, resulting in a 10 MHz scan chain clock and a 5 kHz IO update rate.

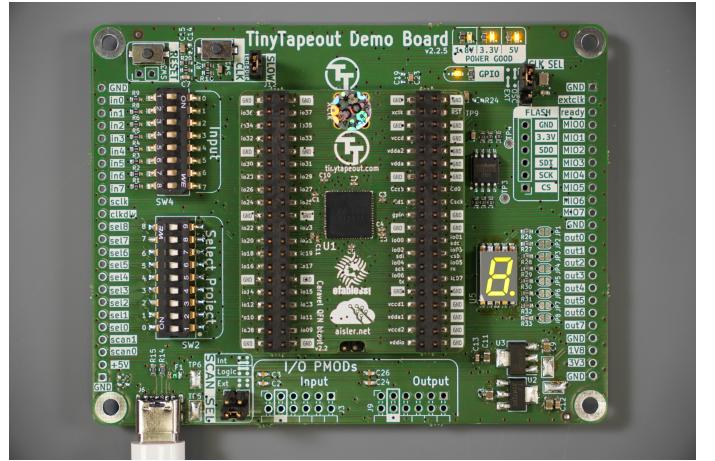


Fig. 9. The demonstration board. Certified Open Source Hardware ES000040 [24].

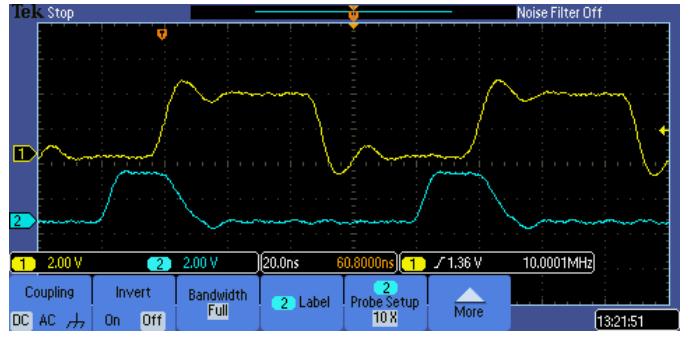


Fig. 10. Measurement from TT02 silicon, with input clock in yellow and the distorted output clock in blue.

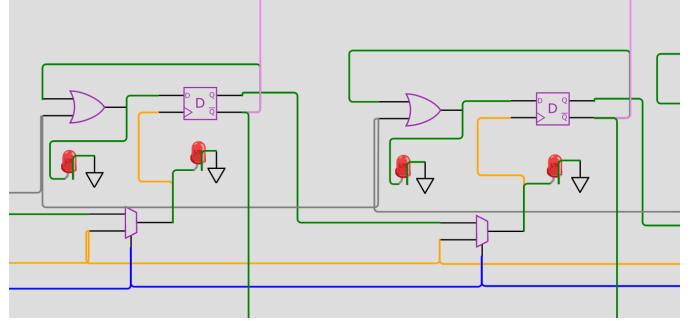


Fig. 11. Combinational logic in the clock path of one of the failed designs.

Some designs didn't function as expected, which in most cases was due to faults in the submitted design.

As well as 82 Verilog designs, 64 used the Wokwi graphical editor, 6 used alternative HDLs like VHDL, Amaranth [26] and Chisel [27]. Some Wokwi designs using combinational logic in clock paths (Fig. 11) worked in simulation but failed in hardware. This was due to the lack of timing data in the simulation, and wasn't detected by STA because the clock paths were not known. A detailed analysis has yet to be carried out.

At the time of writing, PCBs are in production and are expected to ship to customers by the end of January 2024.

Tiny Tapeout 3 silicon was received in January 2024, and

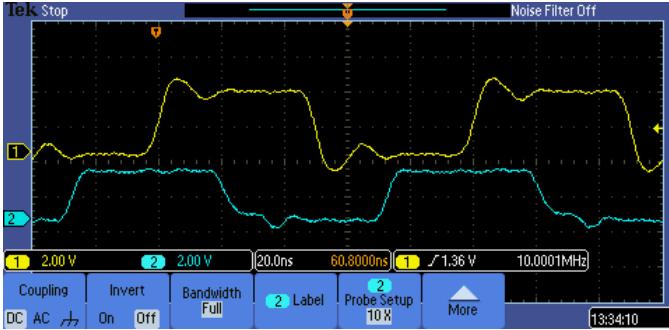


Fig. 12. Measurement from TT03 silicon.

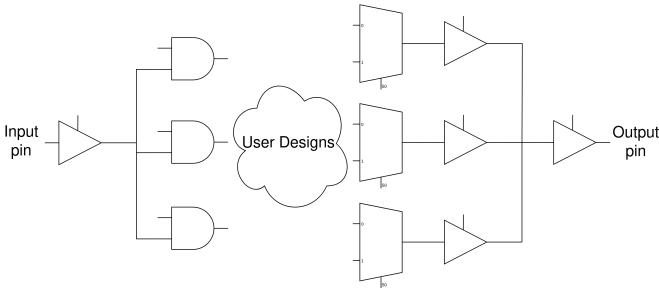


Fig. 13. Simplified diagram of the multiplexer architecture.

the updated scan chain shows a more symmetric (Fig. 12) output clock at the end of the chain. This will allow a faster scan chain clock, resulting in a faster update frequency.

VI. BEYOND THE SCAN CHAIN

The biggest limitation of the scan chain based architecture was the IO bandwidth and latency. A new architecture was needed for TinyTapout 4, so proposals were gathered from the community. An online video call was held and the 10 proposals discussed. The winning design was a fairly straightforward multiplexer design shown in Fig. 13. It was chosen as the simplest to implement while providing the most benefit in terms of additional IOs and higher bandwidth.

The physical layout (shown in Fig. 14) consists of a central controller connected up and down to two vertical spines. Twenty-four horizontal muxes connect to the spine with each supporting 16 designs. This allows up to 384 separate single tile designs. Multiple tile designs were also enabled, allowing a maximum project size of 8×2 tiles or $1359 \times 225 \mu\text{m}^2$ —around 20 000 logic cells. Table II shows the key differences between TT03 and TT04.

Another major limitation of TT01 to TT03 was the small number of IO. The scan controller used 9 GPIOs to select the currently active design, which, while simplifying the demo board, wasted valuable pins. With TT04, the parallel design selection was dropped in favor of a serial protocol. The extra pins were then used as bidirectional pins, giving each design clock, reset, and 24 IO.

An invite-only experimental shuttle [28] was submitted with 32 designs to Efabless chipIgnite 2306C. Two of the designs included a power gate as a stepping stone to supporting analog and mixed-signal designs.

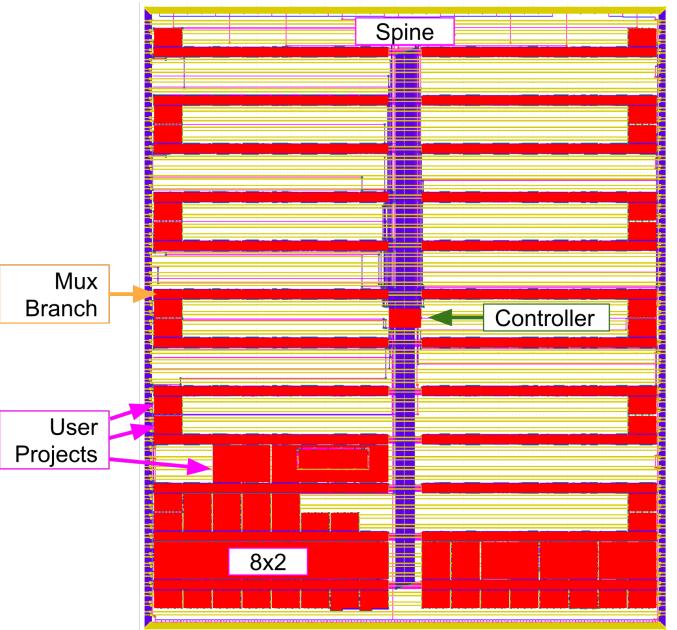


Fig. 14. The TT03.5 test design.

TABLE II
COMPARISON BETWEEN TT03 AND TT04

| Parameters | TT03 | TT04 |
|------------------------|--------------------------------|---------------------------------|
| Max clock speed | 8 kHz | 50 MHz |
| Max design size | $150 \times 170 \mu\text{m}^2$ | $1359 \times 225 \mu\text{m}^2$ |
| Input pins | 8 | 10 |
| Output pins | 8 | 8 |
| Bidirectional I/O pins | None | 8 |
| Custom GDS file | X | ✓ |

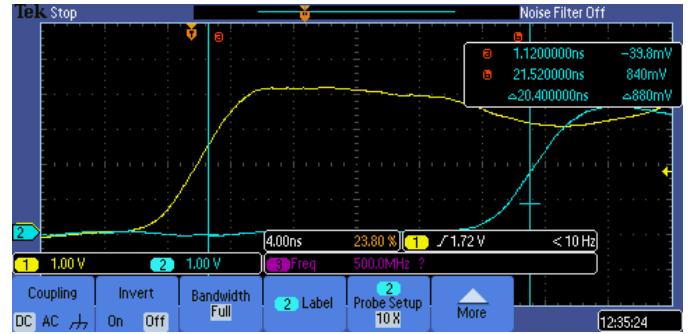


Fig. 15. Round trip latency on a rising edge of about 20 ns.

VII. MULTIPLEXER SILICON RESULTS

After silicon was received, the worst round trip latency was measured to be 20 ns as shown in Fig 15 and 16. Some designs have been validated, including a VGA clock project (Fig. 17) that takes advantage of the new higher speed IO.

The overhead of multiplexing multiple tiles makes power consumption of the infrastructure only a minor concern at this point. We don't have a direct comparison of the power consumption impact of the multiplexer vs. the scan-chain architecture. The motivation of the multiplexer approach is to substantially increase the bandwidth of the IOs.



Fig. 16. Round trip latency on a falling edge of about 16 ns.



Fig. 17. VGA clock design running on TT03.5 silicon.

```
enabling design tt_um_test by sending 102 [0b01100110] pulses
design repo https://github.com/TinyTapeout/tt03p5-test @ 434c5d508d20053bea346881a61355f87ea1ca91
0 0 0 0
1 0 0 0
0 1 0 0
1 1 0 0
0 0 1 0
0 1 0 0
0 1 1 0
1 1 1 0
0 0 0 1
```

Fig. 18. A MicroPython program [30] enabling a design, clocking it, and printing the results.

The new chip pinout and serial design selection required a new demonstration board (Fig. 19) that included an easy way to select the design. The RP2040 microcontroller was chosen as a co-processor as it allows:

- Drag and drop firmware updates on any OS,
- Runs MicroPython [29], ideal for beginners to enable and test their designs (Fig. 18),
- External memory emulation via PIO and DMA.

An additional PMOD expansion port was added for the bidirectional pins, and the community has started to standardize on pinouts [32] making it easier to test each other's designs. A new repository was created to house user-contributed PMODs [33], for example the VGA PMOD shown in Fig. 20.

An additional set of 3 PMOD expansion ports were added that mixed input and outputs, allowing the most common standard PMODs to be used. For more information about the circuit board, pinout and PMOD support see the reposi-

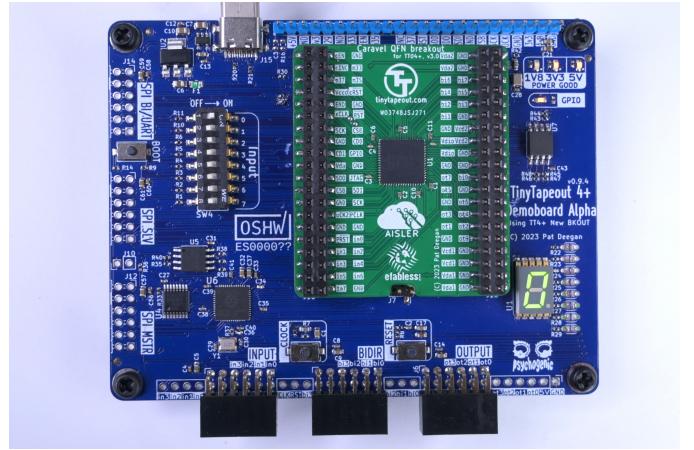


Fig. 19. The TT04+ demo board [31].

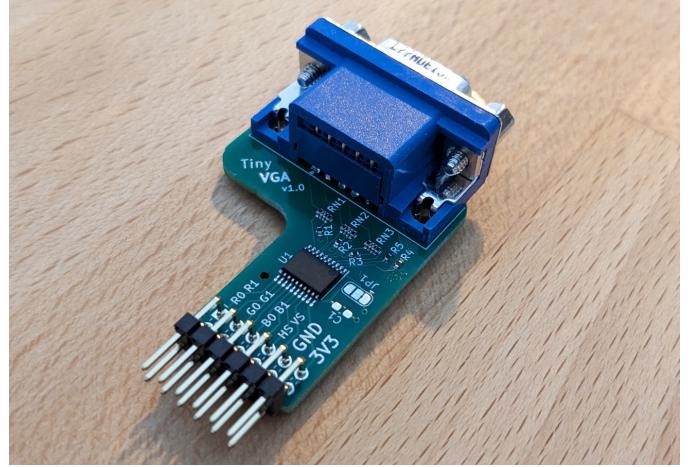


Fig. 20. A user-contributed VGA output PMOD.

tory [31].

VIII. IMPROVING THE MULTIPLEXER AND MIXED SIGNAL SUPPORT

TT05 split the mux into two parts to improve performance. Because of the split, the controller was also updated to mux between the two halves. Some other small changes to the mux including improving STA results by tweaking, adding or removing buffers. As each spine segment is now half as long, it will have half the capacitance. We expect to reduce the round trip latency to around 10 ns.

For TT06, the Caravel harness will be replaced by OpenFrame [34], an alternative harness provided by Efabless that uses the same padding but removes the RISC-V coprocessor. This results in 5 mm² more space for user designs, and 12 more pins that will be used for analog signals.

For increased safety, all designs will be power-gated, which allows designers to take more risks or use custom flows.

Analog and mixed-signal designs will be enabled by adding an analog multiplexer based on transmission gates [35]. This allows up to 192 designs to share the analog pins between them. The transmission gates were tested as part of an experimental analog submission to TT05 shown in Fig. 21.

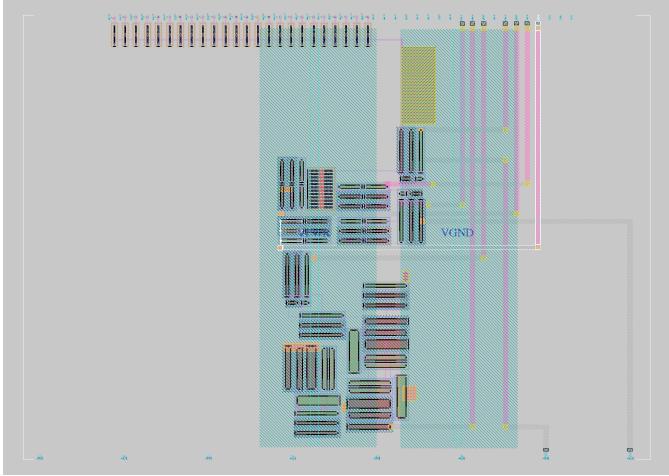


Fig. 21. Ring oscillator and DAC design submitted to TT05 with a transmission gate highlighted (auto-placed and auto-routed using an experimental analog P&R tool).

Noise coupling between analog and digital power domains is a critical concern. However, due to other limitations of our current setup like limited number of low bandwidth analog interfaces, we target educational low-medium performance analog and mixed-signal designs, where noise coupling is a lesser concern.

TT06 is planned to open for digital designs at the end of January 2024, for analog designs at the end of February, and to close on April 19th, 2024.

IX. SILICON SHOWCASE

A small sample of the types of designs possible with Tiny Tapeout are listed below:

- Serial FPGA (Link)
- Synthesizable Digital Temperature Sensor (Link)
- 395 standard cells with mux (Link)
- FM transmitter with I2S input (Link)
- USB full speed - (Link)
- A Linux capable RISCV CPU - (Link)

An index of all submitted designs can be found at [TinyTapeout.com/runs/](https://tinytapeout.com/runs/) [3].

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