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INTERCONNECTED ANALOGY AND RESEMBLANCE: FROM CLASSICAL MUSIC TO MODERN SEMICONDUCTOR TECHNOLOGY

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ABSTRACT

The world is becoming more interconnected and inter-dependent. The technologies of two main semiconductor devices (IC and optoelectronics) are also interacting with each other with more integration and interplay. In this paper, we review the evolution of the two semiconductor technologies based on the analogy of the other two main classical music instruments (violin and piano). We discuss the similarity and resemblance of the two seemingly different fields (semiconductor vs. classical music) and use them as guidance for future roadmap of semiconductor development and integration.

KEYWORDS: Semiconductor Technology, Si IC, III-V Compound Semiconductor, Si Photonics, Classical Music, Violin, Piano

INTRODUCTION

As the world continues to evolve, human beings now have greater adoption to resolve the problems and advance the human civilizations using multidisciplinary approaches. Recently, “Big History” spearheaded by David Christian of Australia’s Macquarie University and promoted by Bill Gates of Microsoft has changed the way people interpret and study history [1]. Instead of only focusing on human history in the time frame of 7,000-10,000 years, the “Big History” expands the timeframe to 13.8 billion years and studies any human fits within the universe. The “Big History” finds analogies among different fields and knowledge spaces.

The semiconductor world is also emerging to the tractions where the digital and non-digital systems are starting to interact with each other [2,3]. The digital chips such as CPU, memory and logic have traditionally followed Moore’s law for the past few decades. The device scaling roadmap has been well defined for each technology node. The semiconductor companies such as Intel and TSMC have been very successfully achieving the increased device function and reduced cost per function. Recently, TSMC has announced volume manufacturing of A9 chips for Apple using 16nm CMOS technology. On the other hand, the device scaling is approaching its physical limit when the technology node reaches around 5nm. Hence, the global semiconductor industry is seeing a new trend called “More-than-Moore” (MtM) where device development is not necessarily limited to the scaling by Moore’s law. The novel MtM technologies would likely incorporate analog/RF, MEMS and optical devices with CMOS-based digital devices.

Unlike the IC where the technology development has been traditionally driven by the Moore’s device scaling, the III-V technology development has been relatively sporadic in terms of roadmap. In the past, the III-V manufacturers have been fabricating optical and optoelectronic components based on specific customer demand in certain niche markets.

Several renowned examples include JDSU's $LiNbO_3$ modulators for switching application, Ortel's analog lasers for community annetena television (CATV) application and most recently Source Photonics' quad small form-factor pluggable (QSFP) transceivers for datacenters.

As the IC is trending towards more versatile MtM, the likelihood to couple the Si and III-V seems to become more feasible. In this paper, we discuss the semiconductor technological development based upon "thinking-outside-the-box" approach. We study the history of the classical music in the past few centuries to find its similarity with the semiconductor history in the past few decades. For the first time, we present the interesting analogy between the two different fields and use the collective learning knowledge to predict the future technology development.

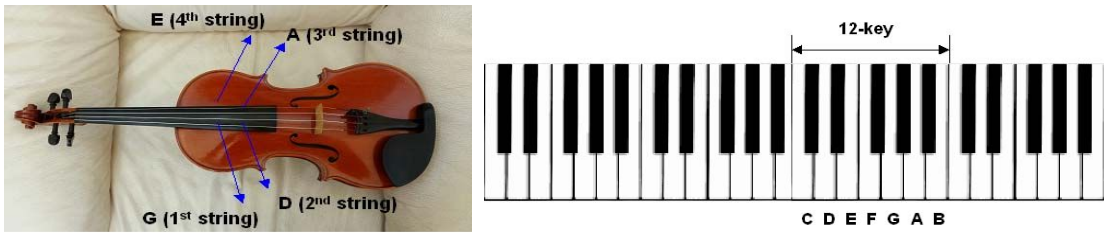
MATERIALS AND METHODS

Indeed, the world has become more inter-connected and inter-dependent than ever [4]. The research fields often show similarities even between two seemingly different fields. One of the examples for such similarity is between classical music and semiconductor technology, as shown in Table 1. Generally speaking, the violin and piano in the classical music are analogously equivalent to the Si and III-V in terms the number of element, history and function role in their respective fields. In the following, we list each of them in details for the background study.

Table 1: Comparison of Classical Music and Semiconductor Technology: Similarity and Analogy

Classical Music		Semiconductor Technology	
Violin	- Less playing range based on roughly 28 notes - Longer history (invented in the 16th century)	Silicon	- Devices primarily based on 1-2 materials systems (Si, SiGe) - Longer history since 1947
Piano	- More playing range based on roughly 52 notes or 88 keys including half notes - Shorter history (invented in the 18th century)	III-V	- Devices based on >10 material systems (InP, InGaAsP, InAlGaP, InGaN, GaAlAs, InGaAs, GaInAsSb, AlN, ZnSe, InGaN, etc.) - Shorter history since 1962

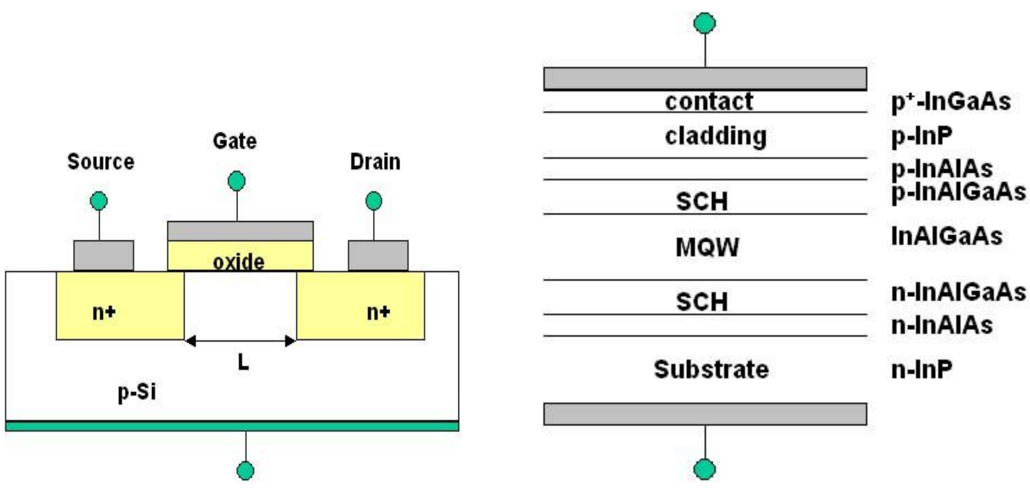
In the classical music world, violin and piano are the two most popular and widely played instruments. The violin was invented in the 16th century. The four violin strings (G, D, A and E) can cover up to about 28 notes, as shown in Figure 1a. The interval between each string is 4 notes where string D is 4 notes higher than string G, string A is 4 notes higher than string D and so on. On the other hand, the piano was invented in the 18th century. The piano keys typically include 52 full notes with a 12-key pattern, as shown in Figure 1b. Including the half notes, the playing range covers a total of 88 keys or more. When we compare the two classical music instruments with the two main semiconductor technologies, we find some interesting and surprising similarities. The violin and piano find themselves striking resemblances and analogies to the Si and III-V, respectively.



(a) (b)

Figure 1: (a) Top View of the Violin Where 4 Strings are Used for the Play The Playing Range Covers about 28 Full Notes (b) Diagram of the Piano Keys Where 12 Key Patterns are Used The Playing Range Covers about 52 Full Notes

First, the III-V device in the semiconductor world is analogous to the piano in the classical music world. Both employ a larger number of elements (larger notes for the piano or greater material systems for the III-V device) compared to their respective counterpart of violin and Si. In addition, both III-V and piano also have similarly shorter history than their counterpart. In the semiconductor world, the Si field-effect transistor is typically based on Si substrate with implantation doping to form the source and drain, as illustrated in Figure 2a [5], while the III-V device is typically based on various material systems to form the active lasing region, as shown in Figure 2b [6-8]. Although the violin and Si are based on a smaller number of elements, both have been playing predominant roles in their respective worlds. As of today, Si devices continue to be the mainstream in the semiconductor market. Companies such as Intel, TSMC, NXP Semiconductor, IBM, TI and Samsung have been relentlessly chasing and extending Moore's Law in the past several of decades in order to realize lower cost and higher functionality [9,10]. For the classical music world, the violin concertos such as Tchaikovsky D major, Op.35, Mendelssohn E minor, Op.64, Bruch G minor, Op. 26 and Sibelius D minor, Op.47 continue to be the most popular pieces played in Hollywood Bowl and other concerts around the world.



(a) (b)

Figure 2: Examples of (a) Si Field-Effect Transistor (FET) with Gate, Source and Drain. (b) III-V Semiconductor Laser with Heterostructure p/n Junction

RESULTS AND DISCUSSIONS

Dual Relationship

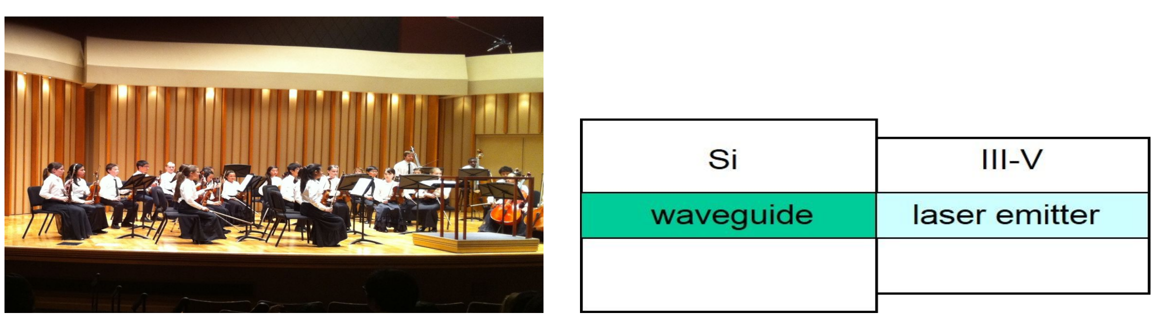
Table 2: Dual Relationship in Classical Music and Semiconductor Technology

Classical Music		Semiconductor Technology	
Violin & piano duo	- Wieniawski, Legende, Op.17 - Paganini Caprice no.24 - Bach Chaconne in D minor - Tchaikovsky piano concerto no.1 - Beethoven piano concerto no. 5, "Emperor"	Silicon & III-V duo	- Hybrid Si/III-V devices - Nanophotonics - System-on-chip (SoC) - Network-on-chip - System-in-package (SiP)

Here, we review the interplay between the violin and piano as well as the relationship between the Si and III-V (see Table 2). One vivid example for the classical music is the duo performance of the piano and violin include the music pieces such as Wieniawski Legende, Op.17, Paganini Caprices No.24, Accolay violin concerto No.1 A minor and Bach Chaconne in D minor. For those music violin pieces where the violin plays the leading role, the piano provides indispensable background to maximize the melody of the violin play. Another successful classical music examples are the piano concertos such as Tchaikovsky piano concerto no.1 in B-flat minor, Op.23 and Beethoven piano concerto no.5 in E-flat major, Op.73. Those pieces are composed for the piano to be the leading role. All those duo-instrumental music pieces have proven to be huge success in the classical music. The beauty and harmony are generated by the melody between the piano and violin instruments.

For the semiconductor technology, there have been several integrated solutions that are emerging in recent years. Examples include hybrid Si/III-V devices, system-on-chip (SoC), network-on-chip and system-in-package (SiP) [11-14]. The SiP contains a number of integrated circuits in a single package or module. The semiconducor devices with various functions can be stacked vertically or horizontally. For the vertical integration, the 3D IC packaging technology is drawing increasing interest. The horizontal integration could involve the coupling of Si and III-V devices.

Figures 3 show comparative illustrations for the duo relationships in the classical music and semiconductor technologies. Figure 3a shows example of the chamber orchestra performed by Colburn School string ensemble student musicians. The orchestra is an instrumental ensemble that contains violin, viola and cello strings as well as piano with percussion instruments. Figure 3b shows the example of system-in-package that incorprates the hybrid Si and III-V devices. The III-V device in this case is the laser emitter, and the Si device serves as the waveguide that transmits the optical signal from the laser emitter.



(a) (b)

Figure 3: (a) Chamber Orchestra from Colburn School String Ensemble
(b) Example of System-in-Package (SiP) such as Hybrid Si and III-V Device

Roadmap for Semiconductor Technology

Now, the question arises about the future development of Si and III-V in MtM technologies. Can they marry together to enhance the functionality with each other? The Si and III-V were originally developed to address the separate needs in the electronics and optical applications. In the past decade, there has been some preliminary development on Si photonics. For instance, Intel announced a high-speed Si optical modulator using metal oxide semiconductor in 2003 [15]. IBM also announced Si photonics for the next generation computing systems in 2008 [16]. If the past success from the violin-piano duo in the music world is of any guide, the monolithic integration of Si and III-V would be expected to be successful in the foreseeable future. The Si and III-V may be coupled together in the form of some hybrid device. One recent example is the hybrid Si photonics device where the wavelength of the III-V laser diode can be tuned by means of the Si channel, as shown in Figure 4 [17]. The temperature of the Si channel can be controlled by the formation of the silicide line formation [18]. Upon the application of high current density to the Si channel, the silicide line originating from the cathode contact can be formed. The length of the Si line formation can be adjusted based upon the bias current. The longer the silicide line that is formed in the Si channel, the lower the overall resistance of the Si channel. Hence, the resistance of the Si channel is bias-controlled, and consequentlly the temperature of Si channel and the adjacent III-V laser diode can be pre-set by the bias. Based on the operating principle, the wavelength of the laser diode can be tuned by adjusting the bias current applied to the Si channel.

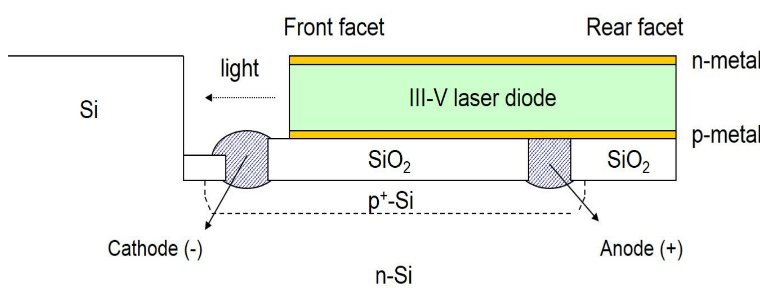


Figure 4: Example of Hybrid Si Photonics that Enable Active Wavelength Tuning Based on Control of Silicide Line Formation in the Si Channel

The broad applications for Si photonics are likely to include light sources, modulators, switches and detectors. At the moment, it is probably still premature to define the roadmap of Si/III-V integration. Nevertheless, the marriage between Si and III-V is poised to happen and promises to be the next generation high performing MtM device. The HELIOS project by the European Commission is yet another example for Si photonics initiative that has been mapped out to 2020 horizon [19-20].

A Path To Interconnected, Collective Learning

There has been an old saying that history repeats itself. As the “Big History” is gaining more popularity, the mankind is likely to increasingly embrace the theory of analogy and resemblance between different fields and learn to enhance their efficiency in collective learning. It is optimistic that human being would continue to evolve to advance the knowledge in order to take the next challenges and to prosper in the Universe. For the semiconductor world, the More-than-Moore may be another successful example in the near future.

CONCLUSIONS

For the first time, we reviewed the evolutions of the two semiconductor technologies (IC and optoelectronics) based on the analogy of the other two main classical music instruments (violin and piano). We found the interesting similarity and resemblance of the two seemingly different fields (semiconductor vs. classical music) in many aspects. If the history of the classical music evolution was a good guide, the future roadmap of semiconductors would be expected to involve more integration and interplay between the Si IC and III-V optoelectronics.

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